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FINAL TECHNICAL REPORT

ADVANCED APPLICATION FLIGHT EXPERIMENTS PRECISION ATTITUDE DETERMINATION SYSTEM

REPORT NO. 22817-6002-RU-00

31 MARCH 1976

VOLUME II
SYSTEM TESTS

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

TRW
SENSE AND SPACE SYSTEMS GROUP

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278



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FOREWORD

This document constitutes the TRW Defense and Space Systems Group final technical report to NASA Langley Research Center for the Application of Precision Attitude Determination Systems to the Earth Resources Survey (AAFE) Program. Prepared under NASA contract NAS1-12894, the report is being presented in two volumes, of which this is Volume II:

- Volume I – Strapdown Star Tracker Development
- Volume II – System Tests.

This report reflects the contributions of a number of previous efforts performed both under NASA contract (NAS5-21111) and independently by TRW. In the area of system design and analysis these efforts are summarized in the following final technical reports:

- PPCS System Design and Analysis, 13900-6012-R0-01, NASA/GSFC, NAS5-21111, 1 July 1972.
- PADS System Design and Analysis (Two-Axis Gimbal Star Tracker), 13900-6014-RU-00, NASA/GSFC, NAS5-21111, 1 July 1973.
- PADS System Design and Analysis (Single-Axis Gimbal Star Tracker), 13900-6016-RU-00, NASA/GSFC, NAS5-21111, 1 July 1974.
- PADS System Design and Analysis (Strapdown Star Tracker), 99994-6316-RU-00, TRW Report, 23 December 1975.

In the area of hardware development the following reports have been published:

- PPCS Star Tracker Test, 13900-6013-RU-00, NASA/GSFC, NAS5-21111, 1 July 1972.
- PADS Star Tracker Test, 13900-6015-RU-00, NASA/GSFC, NAS5-21111, 1 July 1973.

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1. INTRODUCTION AND SUMMARY

Since 1970 TRW has been engaged in activities related to precision attitude determination systems (PADS) for spacecraft applications under company, NASA, and USAF funding. In addition to extensive analyses of such systems, developmental efforts have been undertaken in the areas of star trackers and software algorithms. Engineering model gimbal and strapdown star trackers were developed and tested along with computer simulations of the effectiveness of various algorithm approaches.

In 1974 NASA/LaRC awarded TRW a contract to perform a laboratory test of the performance capability of an engineering model PADS. The test objective which evolved subsequently was to test two such systems, one using a strapdown star tracker, the other using a single-axis gimbal star tracker. The simulated orbit configuration was to be that of a PADS aboard a three-axis stabilized, earth-pointed satellite in geosynchronous orbit. The performance goal was to demonstrate 0.001 degree (1σ) per axis accuracy for both the strapdown and gimbal PADS. A secondary program objective was the fabrication, assembly, and unit test of the strapdown star tracker for the system test. The majority of the design of this tracker had already been accomplished.

A functional block diagram of PADS is presented in Figure 1-1. PADS, mounted aboard a spacecraft, provides estimates of the inertial attitude of the spacecraft axes. The PADS sensors are:

- A star tracker which provides periodic updates of the spacecraft attitude relative to identified stars.
- Gyros which provide a continuous indication of the relative inertial attitude of the spacecraft.

In addition to the sensors, a digital computer (either on-board or ground-based) implements the software algorithms which combine the redundant sensor signals and compute the spacecraft inertial attitude.

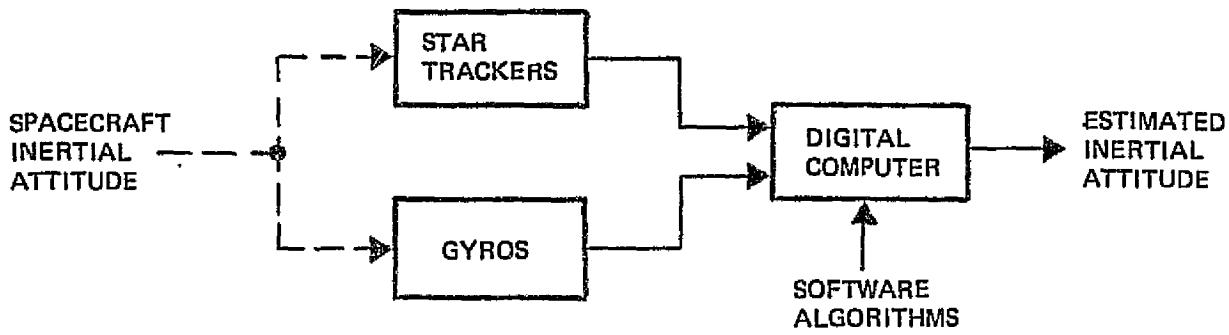


Figure 1-1. Precision Attitude Determination System (PADS)

The PADS engineering model hardware components tested in the laboratory are shown in Figure 1-2. These components consist of:

- A strapdown star tracker developed by TRW
- A single-axis gimbal star tracker also developed by TRW
- A three-axis inertial reference unit furnished by NASA.

The PADS software algorithms were implemented offline in a CDC 6500 digital computer.

In orbit the strapdown star tracker uses the orbit rate of the satellite for star availability. The developed strapdown star tracker has a star magnitude sensitivity requirement of $8 M_V$ in order to provide frequent star updates at geosynchronous rate. A small 1° by 1° field of view resulted from the accuracy requirement of 0.001 degree.

The single-axis gimbal star tracker is a modification of a two-axis tracker developed by TRW on a USAF program. In its modified state it has a $1/2^{\circ}$ by $1/2^{\circ}$ field of view which can be gimbaled through $\pm 45^{\circ}$. In view of the larger effective field of view of the tracker, its star magnitude sensitivity requirement is only $3.5 M_V$.

The original intent was that NASA would furnish an engineering model of a three-axis inertial reference assembly using the Bendix 64 PM RIG gyro. However, schedule difficulties precluded delivery of this assembly, and the engineering model Inertial Reference Unit (IRU) from the Orbiting Astronomical Observatory program was substituted. Although nominally a higher performance unit, a somewhat anomalous behavior of the IRU gyros resulted in it being roughly equivalent to the Bendix specified performance.

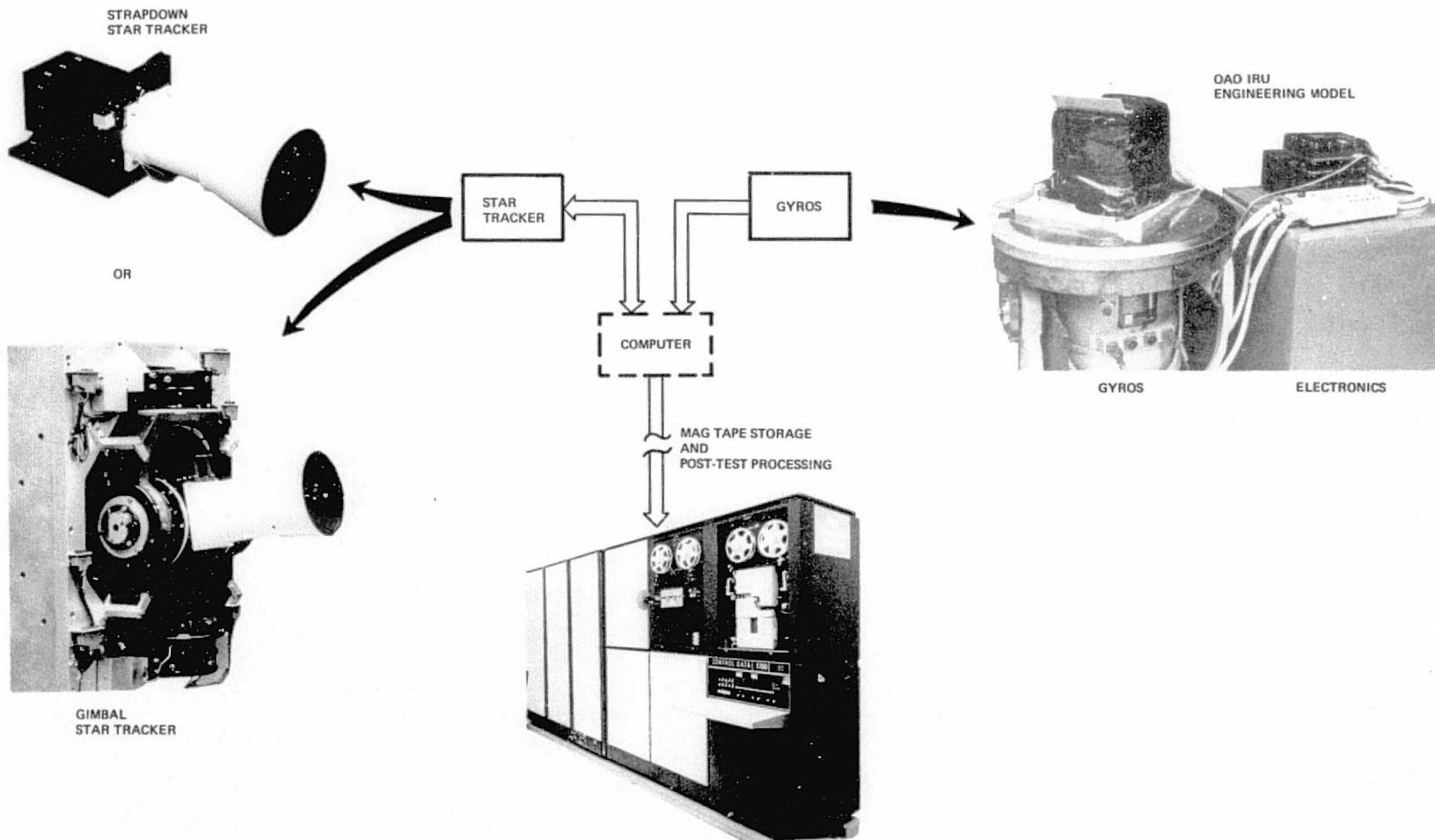


Figure 1-2. PADS Hardware Components

Since the primary emphasis of the laboratory evaluation was on the accuracy of the star trackers and the effectiveness of the software algorithms in processing actual sensor signals, it was considered adequate to implement the algorithms offline in a CDC 6500 digital computer. The sensor signals were time-tagged and stored on magnetic tape during the test, and then processed post-test using FORTRAN coded algorithms.

The precision test facility in which the PADS tests were performed is shown in Figure 1-3. A ground-fixed test configuration was implemented both because of the geosynchronous orbit simulation requirement and the extremely high accuracy demanded from the laboratory instrumentation. In this configuration the PADS reference axes were stationary in the laboratory axes and the collimated star beams were moved relative to the laboratory, or PADS, axes. Knowledge of the inertial motion of the laboratory, plus measurement of the attitude of the star beams relative to the laboratory axes by laboratory instrumentation, provided the reference coordinates against which the PADS attitude estimates were compared.

Both the strapdown and gimbal PADS laboratory tests were successfully completed. In each case a ten day test was performed following an initial alignment procedure. During the ten days four evenly spaced attitude determination test runs were made. Each run was four to five hours long.

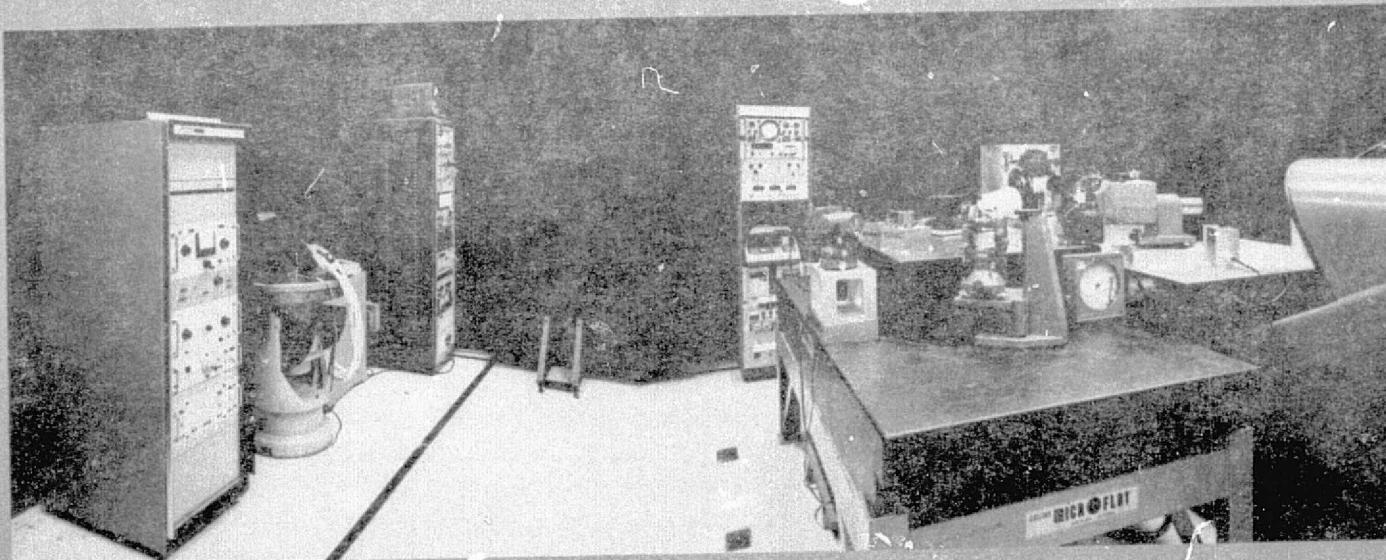
Post-test data processing and evaluation showed that both systems met the performance goal of 0.001 degree (1σ) per axis. Based on star availability data, 20 minute star update intervals were selected to minimize gyro induced errors while still providing a high probability (>97%) of star acquisition. The rms accuracy obtained with each system, normalized to equal components for all axes, was:

- Strapdown PADS: 2.3 arc second (rms) per axis
- Gimbal PADS: 3.6 arc second (rms) per axis.

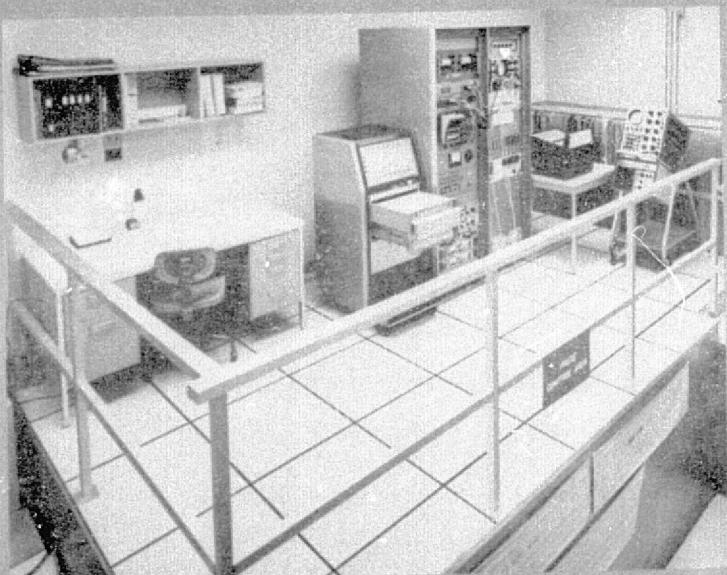
These results were obtained without any limitations in star separation geometry.

In view of the test results obtained, the program was considered very successful, not only because a difficult laboratory evaluation was completed as planned, but because both PADS met their performance goals.

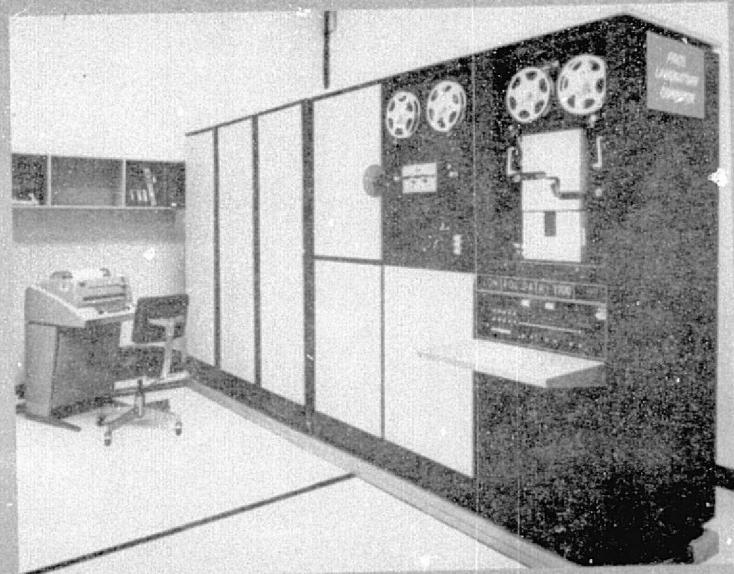
PADSZAFFE
PRECISION TEST FACILITY



LABORATORY



CONTROL AREA



FACILITY COMPUTER

Fig. 1-3. PADS Precision Test Facility.

2. TEST OBJECTIVE

The purpose of the PADS system tests was to measure the performance capability of each of two PADS, one using a strapdown star tracker, the other using a single-axis gimbal star tracker. The performance evaluation was conducted in the laboratory under simulated orbit conditions. These conditions consisted of the stellar optical stimuli and inertial attitude rates which would be experienced on a three-axis stabilized, earth-pointed satellite in geosynchronous orbit.

The primary focus of the evaluation was on the contribution to the total system accuracy by the star trackers, and the effectiveness of the software algorithms in functioning with actual sensor signals.

The performance criteria for the laboratory tests was the accuracy with which the PADS estimated its attitude throughout the test period relative to the inertial attitude of the laboratory at the start of the test. A ground-fixed laboratory test was performed in which the PADS axes remained stationary in the laboratory coordinates. Star stimuli were simulated by moving the star line of sight relative to the laboratory coordinates. A direct means of evaluating the PADS performance was obtained from: 1) true knowledge of the laboratory inertial attitude as a function of time, and 2) precise measurement of the star line of sights relative to the laboratory, and hence inertial, coordinates.

The performance goal for PADS was a steady state accuracy of 0.001 degree (1σ) per axis. For the purposes of this program the one sigma two-axis or three-axis goal is defined as the RSS of the single axis goals.

The laboratory environment was benign in terms of temperature and vibration. No bright object sources were simulated. Satellite attitude control rates were not simulated. Evaluation of these effects was considered more properly relegated to the component test or design simulation level.

3. DESCRIPTION OF PADS

Brief descriptions of the PADS hardware and software are given in this section. Detailed design information for the system components has been documented during previous efforts and programs and is referenced in the following descriptions.

PADS provides estimates of the inertial attitude of its reference axes. A functional block diagram of PADS is shown in Figure 1-1. The star trackers provide periodic absolute attitude updates. The gyros provide continuous relative attitude data. The computer implements the software algorithms which combine these redundant sensor signals and estimate inertial attitude.

The following paragraphs describe in detail the specific PADS components which were tested. Descriptions of the strapdown star tracker, the gimbal star tracker, and the gyros are given along with comments regarding their origin and level of development. In view of the offline data processing which was performed, a description of a flight suitable digital computer was not relevant. The software algorithms are described, but their adaptability to a flight computer is not discussed, again because it was not relevant to this test program. This latter topic has been covered, however, in previous studies described in the foreword.

3.1 HARDWARE

The PADS hardware which was tested in the laboratory is illustrated in Figure 1-2. Two PADS configurations were tested, one using a strapdown star tracker, the other a gimbal star tracker. The same inertial reference unit was used for each configuration. This unit contained three gyros which had their input axes mounted orthogonal to each other. Since the emphasis of the test program was directed toward the performance capability of the star trackers and the effectiveness of the software algorithms, a flight-suitable computer was not used. Instead, the sensor data was collected on magnetic tape during the test using a CDC 1700 computer, and then processed post-test using a CDC 6500 computer.

3.1.1 Strapdown Star Tracker

An extensive description of the strapdown star tracker (SST) is presented in Volume I of this report. Detailed descriptions of the design are given along with extensive design analyses and test results.

The star tracker is a high accuracy, high sensitivity sensor with the performance characteristics listed in Table 3-1. The tracker has been designed to meet the PADS requirement to track 8 M_v stars with 3 arc seconds accuracy. Engineering model level of development has been achieved.

The star tracker uses an image dissector tube as its basic detector because the high sensitivity and resolution available from this instrument is consistent with the PADS requirements. The ITT F4012 image dissector was selected because of its proven reliability in space applications.

Table 3-1. SST Design Parameters

Field of View	1° by 1°
Sensitivity	10 Mv GO(6000°K)
Photodetector	
Type	ITT F4012
Usable Photocathode Area	12.7 mm
Aperture Diameter	0.254 mm
Optics	
Type	Cassegrain
Focal Length	50.8 cm
Aperture	60 cm ²
Instantaneous Field of View	103 arc sec
Electronics	
Position Output	12 bit serial word
Magnitude Output	10 bit serial word
Update Time	0.1 sec
Functional Performance	
Maximum Acquisition Time	13.6 sec
Maximum Track Rate	0.02 °/sec
Accuracy (with FOV and Temp. Comp.)	
Line of Sight to EO Axes	
Noise (1σ)(single sample)	3.0 arc sec (8 Mv)
Fixed (1σ)	2.0 arc sec
EO Axes to Optical Reference	
Bias (3σ)	5.1 arc sec
Bias Stability (3σ)	1.3 arc sec
Size	12.7 x 12.7 x 56 cm
Weight	5 kg
Power (using CMOS logic)	4.6 watts

Photon counting is used as a detection technique because it provides superior sensitivity over that achievable with conventional analog techniques.

The search, track, and mode control electronics are completely digital, not only to complement the photon counting technique, but to eliminate those errors associated with the conventional analog implementations.

The entire electro-optical structure has been made from graphite/epoxy composite material in order to minimize all thermal distortions. This material has a linear coefficient of thermal expansion which is 100 times less than that of aluminum.

A functional block diagram of the SST is shown in Figure 3-1. An explanation of the diagram is facilitated by considering four functional groupings:

- Signal generation
- Acquisition
- Track
- Control.

Signal Generation. Photons received from the star or target are focused by the optics to a spot on the photocathode of the image dissector. The resulting signal from the anode of the tube is processed by the video detector. For weak signals, the output of the video detector will be logic level pulses corresponding to the emission of electrons from the photocathode. For strong signals, in the presence of the cruciform spatial modulation pattern, the output will be a squarewave at the modulation frequency.

Acquisition. Acquisition is achieved by scanning the 1° by 1° FOV with a discrete raster pattern produced by the acquisition scan generator. For normal acquisition the pattern is a 64×64 dot matrix which is completed in less than 14 seconds. Proximity to a star is detected by the star presence circuit. This circuit counts the number of photoelectrons at each dwell point in the scan matrix. In the presence of a star, a dwell count significantly higher than the background noise count will be measured. By commanding the differential count necessary to indicate a star, stars equal to or greater than selected magnitudes may be acquired and tracked.

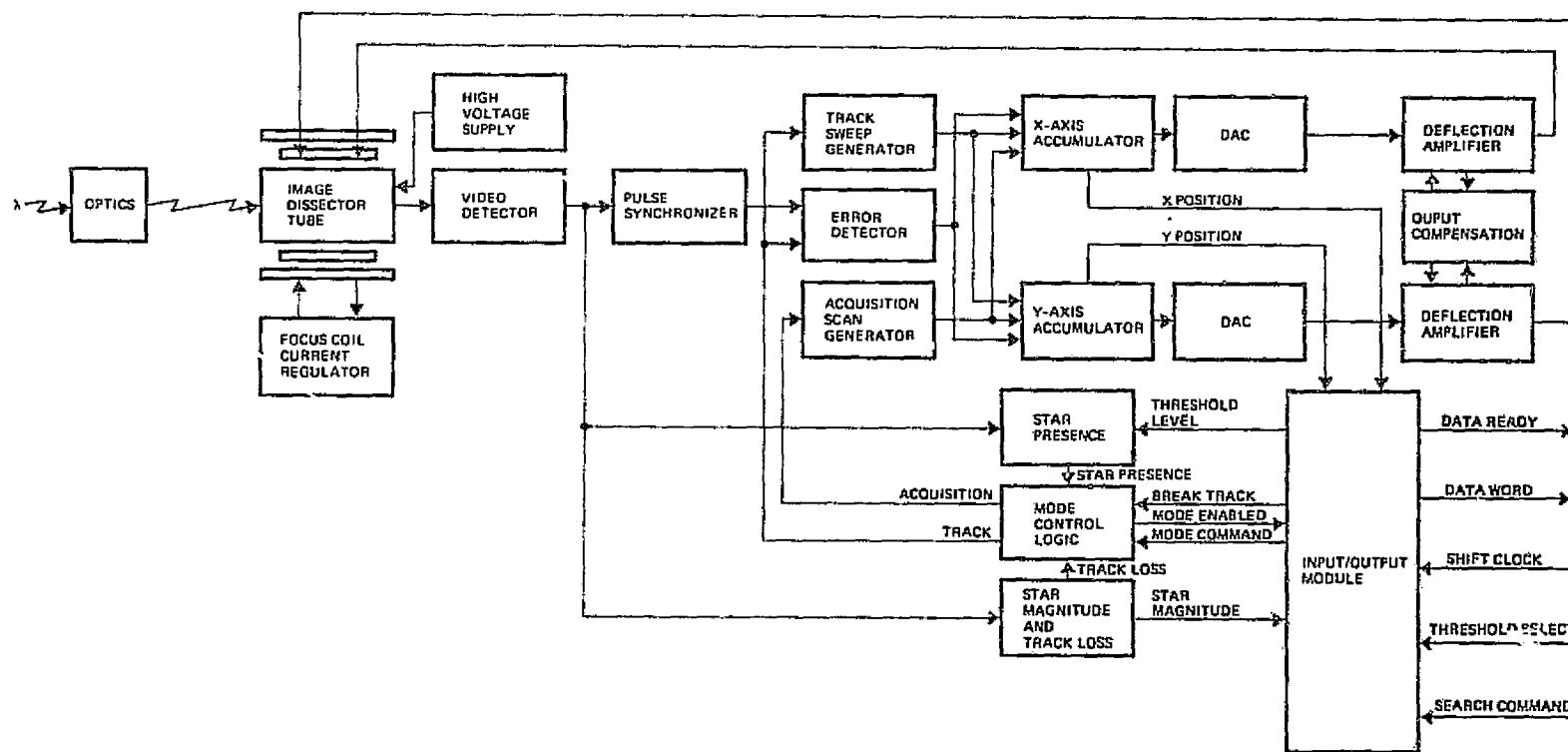


Figure 3-1. Star Tracker Block Diagram

Track. Track is initiated by a signal from the star presence circuit. The track sweep generator starts eight continuous cruciform patterns at the position at which track was entered. If the star magnitude and track loss circuit does not indicate that a star is being tracked, then the acquisition scan is continued. The pulse synchronization circuit is the key element in enabling the tracker to track either bright or dim stars. In the case of dim stars, the circuit will produce pulses on a one-to-one basis with photo-electron pulses. By counting pulses in synchronization with the cruciform track sweep, the percentage duty cycle of the pulse width modulated (PWM) information is computed in the error detector circuit. On the other hand, bright stars will produce a squarewave at the video detector output which reflects the PWM information. By gating this signal with a high frequency clock, the information content is retained in the form of clock pulses instead of photoelectron pulses, and the percent duty cycle is again computed in the error detector circuit. By timesharing the error detector only one circuit is needed to compute the error for both axes. At the end of each cruciform pattern the computed error for each axis is summed with the number in the accumulator for that axis. Each accumulator drives a DAC which in turn drives the deflection amplifiers. Star magnitude is measured by the star magnitude and track loss circuit.

Control. The tracker mode control is implemented by the mode control logic. The inputs to this circuit are:

- 1) Star presence
- 2) Track loss
- 3) Search
- 4) Zero.

The last two signals are manual controls. A manual switch to disable the track loss signal is also provided.

3.1.2 Gimbal Star Tracker

The PADS requirement is for a single-axis gimbal star tracker. However, programmatic considerations necessitated the use of a two-axis star/landmark tracker developed under an Air Force contract. A detailed design description of this unit is given in reference. (1) To make the tracker compatible to

the PADS requirements, the outer gimbal was mechanically locked and the landmark function was inhibited. The remaining star tracker functions represent the same technology developed previously by TRW for a single-axis gimbal star tracker.(2) The following description applies only to the modified tracker.

The PADS gimbal star tracker (GST) consists of a Star Sensor Unit (SSU) mounted within a single degree of freedom Sensor Gimbal Unit (SGU). The SSU incorporates the optics, detector, and supporting electronics. The SGU is an exceptionally precise and stable mount providing gimbal drive for null tracking stars and precision angular readout of the gimbal. The GST interfaces with the Sensor Electronics Assembly (SEA) which provides the gimbal angle processing and servo drive signals. The performance characteristics of the GST are shown in Table 3-2.

3.1.2.1 Star Sensor Unit

The SSU is a high accuracy star sensor designed to track $3.5 M_V$ stars with arc second accuracy. The SSU uses an image dissector tube together with conventional analog search and track electronics.

The optical design results from a tradeoff between the desire for a short focal length to obtain small size and weight, and the requirement to maintain arc-second level accuracy. The selected design is a Cassegrain telescope utilizing aluminum optics.

A bright object sensor and shutter assembly are incorporated in the sensor along with the high voltage power supply. The high voltage power supply will be incapacitated by the bright object sensor when the sun is within the 45 degree field, and also, a rotary solenoid will be actuated which will close the shutter in front of the photocathode.

The sensor assembly has been designed with great care for thermal symmetry to provide maximum thermal-mechanical stability. In particular, the electronics are equally spread around the tube assembly. The high voltage power supply and line voltage converter, behind the tube assembly and the flange mounting, provide symmetrical heat transfer through the structure into the mounting plate.

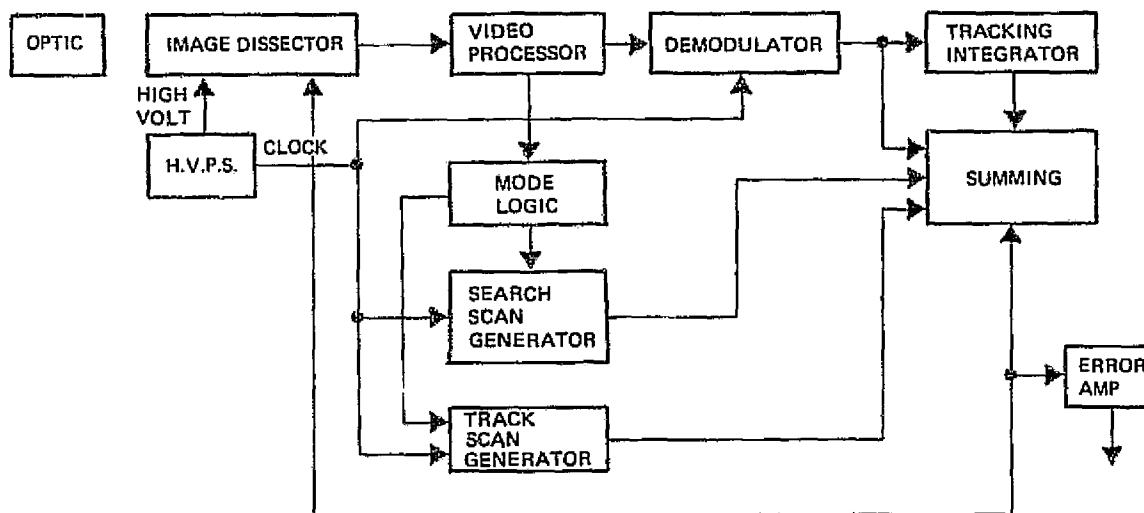
Table 3-2. GST Design Parameters

Field of View	0.5 x 0.5 deg
Gimbal Freedom	Up to ± 60 deg
Sensitivity	+3.5 mV
Bandwidth	25 Hz
Optics	
Focal Length	84 cm
Aperture	54 cm ²
IFOV	84 arc sec
Detector	F4012 RP
Minimum Sun Angle	45 deg
Accuracy ($\Delta\alpha$, per axis)	
Sensor	
Electronic Bias	0.14 arc sec
Thermo-Mechanical (Random)	0.46 arc sec
Noise Equivalent Angle	1.2 arc sec
Gimbal and Encoder	
Alignment	0.71 arc sec
Thermo-Mechanical Stability	0.28 arc sec
Inductosyn	0.86 arc sec
Readout Electronics	
Bias	0.42 arc sec
Random	0.42 arc sec
Noise and Quantization	0.3 arc sec
Size	30 x 51 x 16 cm
Weight	13.6 kgm
Power	17 W

The image dissector, deflection yoke, focus coil, and high voltage biasing network are all contained in a single, integral, encapsulated assembly. The outer structure of this assembly consists of the necessary magnetic shielding to prevent stray fields, or the earth's field, from affecting the image dissector, and is mechanically indexed directly to the optics. The electronics are contained on four flex-print interconnected printed circuit boards which are installed in the housing as a subassembly around the tube assembly.

A functional block diagram of the SSU is shown in Figure 3-2. The following paragraphs explain the sensor operation.

Video Processor. The video processor performs the following functions. During the search mode, automatic gain and threshold control circuits select only the largest video pulse present and send it to the mode control logic. When in the track mode of operation, the image dissector video is shaped into a digital pulsewidth-modulated signal and is fed to the demodulator. A digital star-presence signal and an analog star-magnitude signal are also developed.



(ONLY ONE ERROR CHANNEL IS SHOWN)

Figure 3-2. Functional Block Diagram of Star Sensor Unit

Mode Control Logic. The mode control logic establishes the mode of operation: search or track. The timing of the search cycle, the gating of the tracking loop, and search-scan waveforms are also controlled by the mode logic.

Demodulator. The demodulator circuits consist of timing gates to process the pulsedwidth-modulated video and precision voltage switches which develop the tracking loop correction error voltage at the input to the tracking integrator.

Tracking Integrators. This circuit consists of an integration stage (op-amp) which provides correcting dc voltages to the deflection generator to keep the star image centered in the image-dissector aperture by taking the integral of the error demodulator output.

Scan Generator. The scan generator provides three separate circuit functions. A triangular waveform is generated by a counter-integrator combination and is used as the track mode scan waveform. Two binary counters and D/A converters are used to develop the staircase-type search mode scan waveforms. The above scan waveforms and the dc-correcting voltage from the tracking integrator are summed in current dividers to provide the deflection coil current required.

Error Amplifier. The dc component of the deflection coil current is determined by a current sampling resistor and the corresponding voltage is then amplified and filtered to give the required output pointing error gradient.

3.1.2.2 Sensor Gimbal Unit

The single degree of freedom gimbal assembly utilizes a proven single ball/flexure suspension system and Inductosyn readout. The gimbal is formed by identical drive housing assemblies attached on each side of the star sensor unit. The drive housings incorporate the suspension/bearing system, drive motors, Inductosyn encoders, and data link.

The use of identical drives on both ends of each axis is motivated by the desire to obtain mechanical and thermal symmetry. The star sensor mass is centered between the supporting bearings of the gimbal. Nearly identical

power dissipation in each housing minimizes thermal gradient variations. Further, zero structural slope mounting points are chosen so that one-g distortions result in translation only – not in angular rotations. With this approach, testing can be accomplished with negligible errors due to gravity induced droop.

Gimbal Suspension

The gimbal design features a one-ball bearing configuration. The geometry of this scheme provides self-alignment features and facilitates the fabrication of the gimbal system by providing inherent reference for the establishment of the rotational axis of the gimbal.

The desired axis is established by a line of contact of the balls with the cone surfaces of their retaining cups. The accuracy of the gimbal axis is set by the cups radii of contact and the ball sphericity. Since the ball sphericity can be obtained to two parts in a million and the cups radius of contact is established by lapping, and since all other critical surfaces are indexed to the payloads balls, the achievement of very accurate alignment is possible. The suspension consists of two single spherical balls supporting the payload. Each ball locates itself via two cone type cups. One cup (rotating retainer) is located on each side of the payload and the other cup (stationary retainer) is inclined 40 minutes of arc with respect to the center line passing through the centers of the spherical balls; the stationary cup cone is eccentrically offset with respect to the centerline of the cylindrical shaft containing the cone. The shaft element is housed in the bore of the flexure, which is an intermediate element between the retainer and the gimbal frame.

Drive Motors

Each gimbal motor drive assembly is identical in performance and general configuration. It consists of a two phase permanent magnet motor and appropriate support structure. The motor has 24 poles and 4 skewed slots between pole spaces. The commutation to the motor is provided by the Inductosyn resolver signal which is conditioned to provide the required power in terms of sine and cosine functions with periods satisfying the number of poles (12 speed). Interconnecting of the sine and cosine inputs to the respective motor winding results in a brushless motor exhibiting dc torquer characteristics.

Inductosyn Encoders

The angular rotation of each gimbal is measured using a precision Inductosyn. The Inductosyn is a pair of discs, in this case 5 inches in diameter, which are mounted such as to rotate coaxially with respect to one another with facing surfaces in close proximity. The facing surfaces have printed conductors, forming winding circuits which may be flux linked, disc-to-disc. One disc, designated the rotor, has a single winding; the other, the stator, has two windings. The winding geometry is arranged so that the transformation coupling from rotor to stator varies trigonometrically with relative disc rotation. The two stator windings are in mechanical quadrature to one another. Thus, the device is electrically identical to a synchro resolver, except for a very low coupling efficiency and for a larger number of poles than are normally found in a conventional resolver.

Data Link

The data link provides transmission of electrical signals across the gimbals without excessive restraint torques. The design utilizes an "S" folded conductor strip which is attached at the ends of and slides between a cylindrical stationary member attached to the housing sleeve and a smaller diameter cylindrical component (the rotating member) attached to the motor shaft. The inner and the outer members are lined with nylon rings to provide electrical insulation and mechanical guide for the rolamite action of a 6 conductor strip. There are four such strips providing the capability of $\pm 60^\circ$ motion with restraints not exceeding 36 gm-cm. Both the stationary and the rotating members of this assembly are made from beryllium. Appropriate electrical connectors (miniature) are attached to the periphery of the rotating and stationary component. The data link itself is so designed that it can be removed from the system without disturbing the various electrical interconnections.

3.1.2.3 Sensor Electronics Assembly

The Sensor Electronics Assembly provides encoding of the Inductosyn gimbal angle signals and implements the controller/drive for the gimbal motors. Figure 3-3 shows the SEA functional block diagram for one of the two gimbal axes. The Inductosyn Electronics has as its function the excitation and processing of both multi-speed and single-speed Inductosyn output signals to derive the precision measure of gimbal angle. The Drive Electronics provides for loop compensation and appropriate commutation, and motor power drive functions.

Inductosyn Electronics

An Inductosyn is analogous to a resolver. It has a primary, the rotor, which is sinusoidally excited at some frequency, 10.3 kHz in this case. It has two secondary (stator) output signals of the same frequency, whose amplitudes are trigonometrically amplitude-related to the device's mechanical angle:

$$V_s = kV_e \sin n\theta \sin \omega_e t$$

$$V_c = kV_e \cos n\theta \sin \omega_e t$$

where θ is the mechanical angle, V_e is the rotor excitation amplitude, and ω_e is its frequency. The transformation ratio, k , is extremely small for an Inductosyn, such that the output signal is only a few millivolts. Each Inductosyn has a single-speed and a 256 speed set of windings. The speed ratio, n , is unity for the single-speed section and 256 for the multi-speed section. Thus, the single-speed outputs advance one electrical revolution for each mechanical revolution, while the multi-speed signals advance 256 electrical revolutions for the same mechanical rotation. By processing both pairs of signals an extremely high resolution can be achieved.

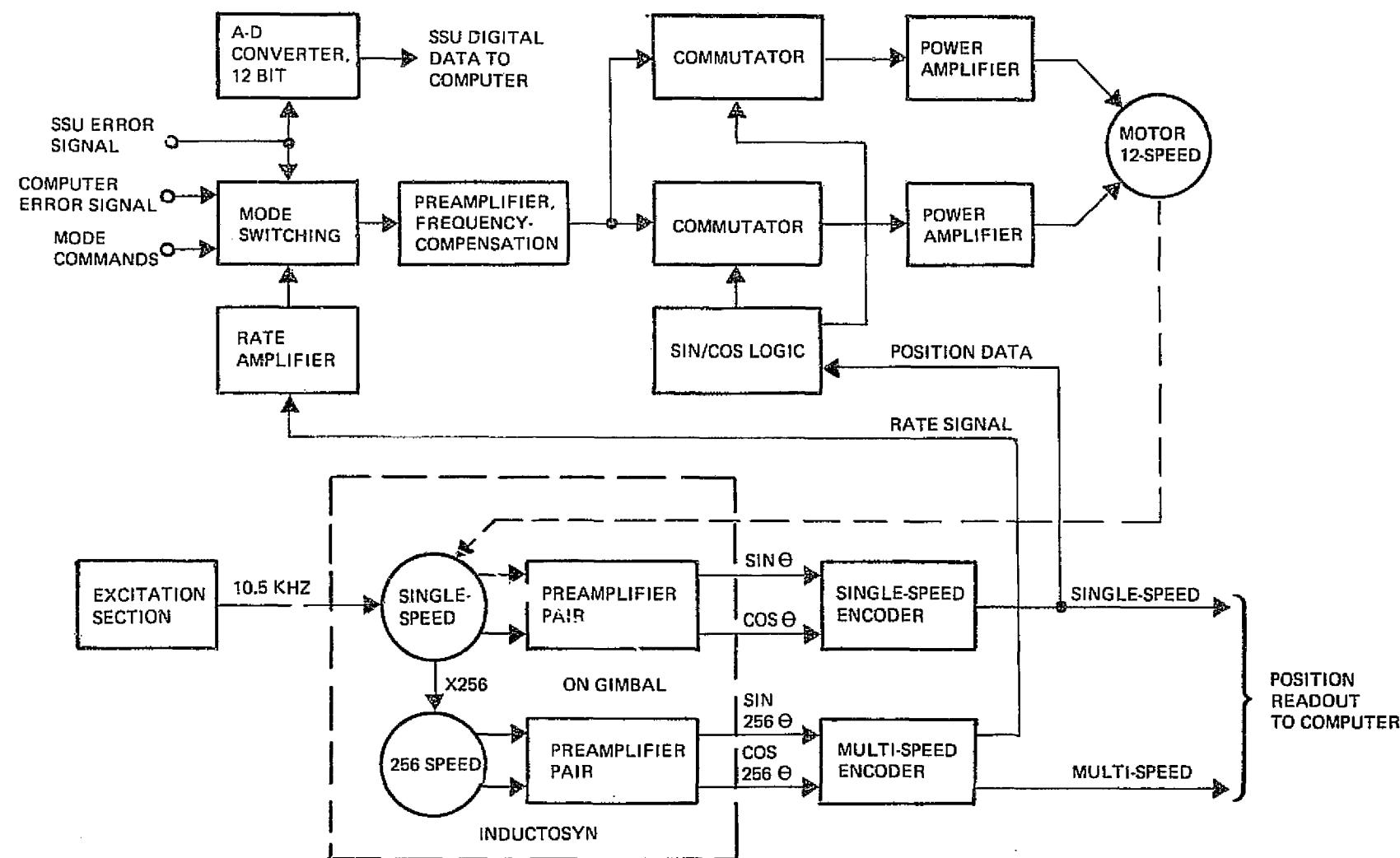


Figure 3-3. Sensor Electronics Assembly Functional Block Diagram

The Inductosyn signals are amplified by special preamplifiers located on the gimbal, and the resultant signals transmitted to the SEA for further processing. Within the SEA, the signals are converted from amplitude to phase format. Each pair, as described above is converted to a phase pair:

$$V_A = V \sin (\omega_e t + n\theta)$$

$$V_B = V \sin (\omega_e t - n\theta)$$

Thus, gimbal angle information now resides in the relative phase of the signals, in "double-angle" form, i.e., the relative phase between V_A and V_B changes twice as fast as $n\theta$. These signals are then converted to standard logic signals, A and B, for use by the encoder logic. The amplitude-to-phase converters are specially designed to preserve the inherent Inductosyn accuracy. A computer analysis has shown a worst-case error of ± 0.03 degree electrical for the converter itself, excluding pre-amplifier gain variations and zero-crossing detector propagation delay variations.

The Encoder section is used to digitally measure the relative phases of the A and B signals from the amplitude-to-phase converters, and thus, to develop a digital quantity representing the gimbal angles.

Gimbal Control Electronics

The control electronics has two modes which are commanded by an external computer:

- 1) Slew
- 2) Track.

In the slew mode a servo summing junction is implemented in the computer using the desired position profile and the SEA inductosyn readout. The error signal from this junction is used to drive the gimbal servo electronics. A rate signal can also be commanded by the computer to augment the gimbal response performance. Operationally, this mode is used to position the gimbal so that a star will be in the field of view of the SSU.

If the SSU acquires a star, it will send a track signal to the computer. The computer in turn will command the gimbal control electronics into the track mode. Here the vertical deflection signal from the SSU is used as the error signal to the gimbal servo electronics. The electronics will drive the gimbal motor until the SSU signal is nulled, i.e., the star is positioned midway between the top and bottom of the field of view.

The servo design consists of a proportional plus integral mechanization which eliminates gimbal hangoff due to static bearing friction. In both modes the servo is damped by a rate signal derived from the inductosyn information. The rate loop is also implemented with a proportional plus integral design to compensate for running bearing friction.

3.1.3 Inertial Reference Assembly

The original plan for the PADS program was to receive a gyro assembly for the laboratory tests from NASA/Goddard Space Flight Center (GSFC). This assembly would have used the Bendix 64 PM RIG gyro in a configuration similar to that for the International Ultraviolet Explorer Satellite. However, procurement difficulties experienced by GSFC prevented use of this gyro assembly on the PADS program. In its place GSFC substituted an engineering model version of the Orbiting Astronomical Observatory Inertial Reference Unit (OAO/IRU). A detailed design description of this unit is given in reference (3). The following description is extracted from this reference and is limited to only those aspects relevant to the PADS testing.

3.1.3.1 General Description

The IRU used in the laboratory tests consists of two packages: an Inertial Package (IP) and an Electronics Package (EP). A test console was also supplied by GSFC which provided an electronic interface capability with the IRU.

The test console provided all the necessary commands and power to operate the IRU. Aside from the start-up and shut-down procedures, the only interfaces with the test console during the PADS tests were manual changes to the R-Term compensation for all three gyros. These changes simplified the quick look display of the gyro performance during the testing.

A data interface unit was added to the test console by GSFC to transmit the gyro outputs to the PADS data collection system. Each output consists of a 16 bit word representing the inertial rotation about the gyro input axis. The scaling is nominally 0.075 arc sec/count. The 16 bit word turns over after approximately 1.4 degrees.

IP

The IP is a temperature controlled cube 9 inches on a side. It weighs 18 kg and contains three precision gyros, their control and readout electronics, a frequency source assembly which provides the precision frequency for all the electronics in the IRU and temperature control electronics. Attached to the IP are radiator plates which conduct heat away from the IP. Each radiator is approximately 7.6 x 22.9 cm in area.

The gyros mounted in the IP were fabricated at MIT. They are MIT designed adaptations of the inertial grade 2FBG-6F floated gyro. The 2FBG-6F gyro was modified for the OAO mainly by simplifying its construction and by improving its data bandwidth capability. The gyros are operated with binary pulse restrained torque loops. Torque data from the gyros are processed as rate integrals (i.e., angles) in the EP and converted to digital signals. The IRU's reference position about each axis can either be reset or changed incrementally. The resets are enabled by programmed commands. Incremental changes in position are limited to one axis at a time.

For the PADS tests the IRU was operated only in the HOLD mode. During this mode, the rate capability is 15 arc sec/sec, or earth rate. The indicated rate of each gyro output can be digitally compensated in the EP (referred to as R-Term compensation).

The gyro electronics, temperature control, and frequency source electronics consist of potted cordwood modules and discrete components, assembled into the following subassemblies: Frequency Source Assembly, Temperature Control Assembly, Auxiliary Temperature Control Assembly, Torque Generator End Assembly (TGEA) and Signal Generator End Assembly (SGEA). Each gyro has a TGEA and SGEA mounted with it, and tuned to it, to provide proper gyro parameters. A total of 21 cordwood modules is used in each IP.

EP

The EP is a rectangular assembly, 22.9 x 38.1 x 15.2 cm weighing 17.3 kgm, made up of 3 electronic trays and an annex attached to tray 1. Contained in the 3 trays and annex are 63 potted cordwood modules and a number of discrete components, power transistors, transformers etc.

The EP contains analog, digital and hybrid electronics. There are 17 major electronics blocks including: power supplies, control units, input/out units, logic and conditioning units.

3.1.3.2 IRU Performance

The IRU was tested at GSFC by personnel from Charles Stark Draper Laboratory prior to delivery to TRW for the PADS tests. This testing is described in Appendix C of this report. In summary, the tests showed that the performance of all three gyros was degraded. The z(yaw) gyro was especially bad.

Following setup and integration at TRW, the IRU performance was again observed and found to be different from that measured at GSFC. This encouraged efforts to improve the IRU. Two actions undertaken did improve the performance:

- 1) A rewiring of the power interface
- 2) A change in the thermal configuration.

The performance was again measured by CSDL and found to be significantly improved. These results are also described in Appendix C.

The gyro performance is described in Appendix C in terms of power spectral density (PSD) curves. Another method which was used to characterize the random drift of the gyros is to plot the standard deviation of the gyro attitude as a function of sample time. Figure 3-4 illustrates the approach which was taken. The standard deviation was calculated as:

$$S = \left[\frac{1}{N} \sum_{i=1}^N \left(\Delta\theta_i - \frac{1}{N} \sum_{j=1}^N \Delta\theta_j \right)^2 \right]^{1/2}$$

where

N = the total number of samples

$\Delta\theta$ = the attitude change over a sample time Δt .

Figures 3-5 through 3-7 show the standard deviation plotted as a function of sample time for the three gyros. The data was derived from two runs taken on 5 September 1975 and 19 September 1975. The first run duration was three hours and gyro attitude was recorded every one second. The second run duration was 60 hours and the data was recorded every 100 seconds. When available, 50 samples were used to compute the standard deviation.

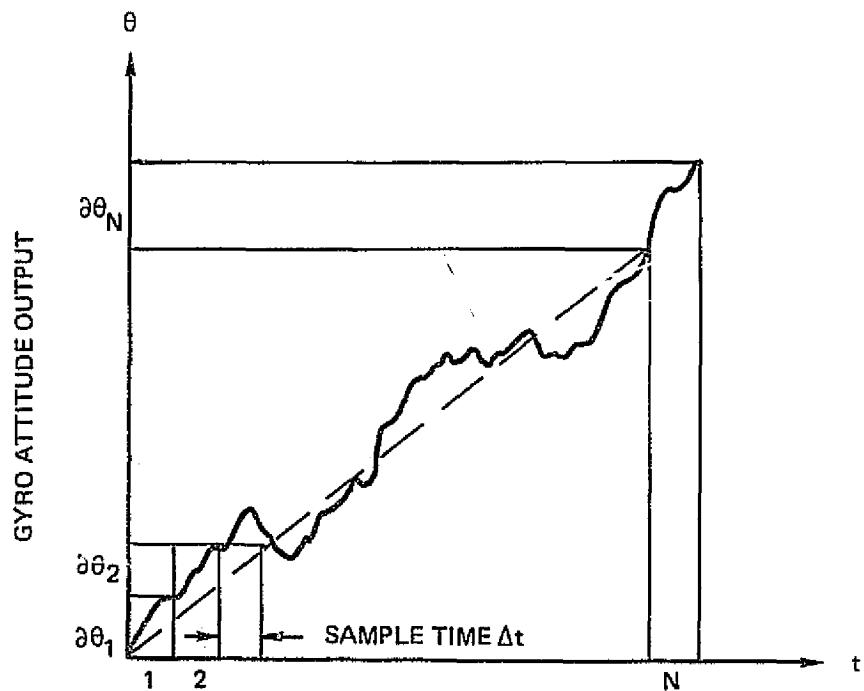


Figure 3-4. Characterization of Gyro Random Drift

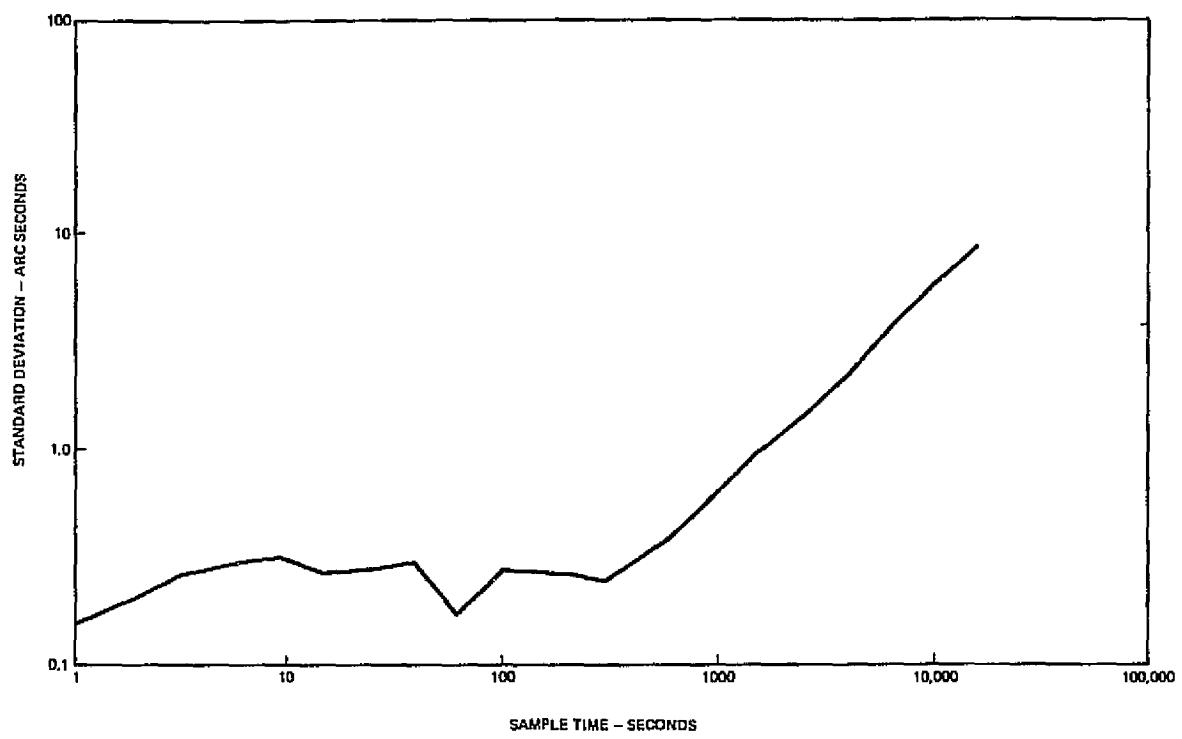


Figure 3-5. X Gyro Random Drift

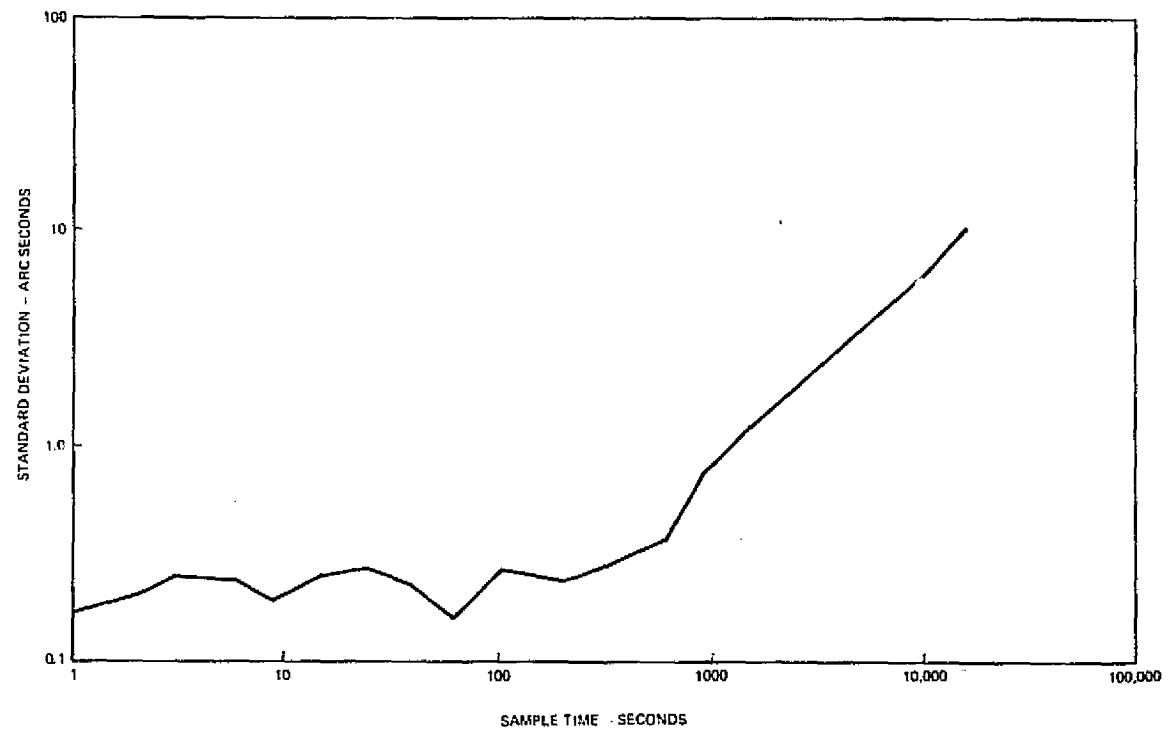


Figure 3-6. Y Gyro Random Drift

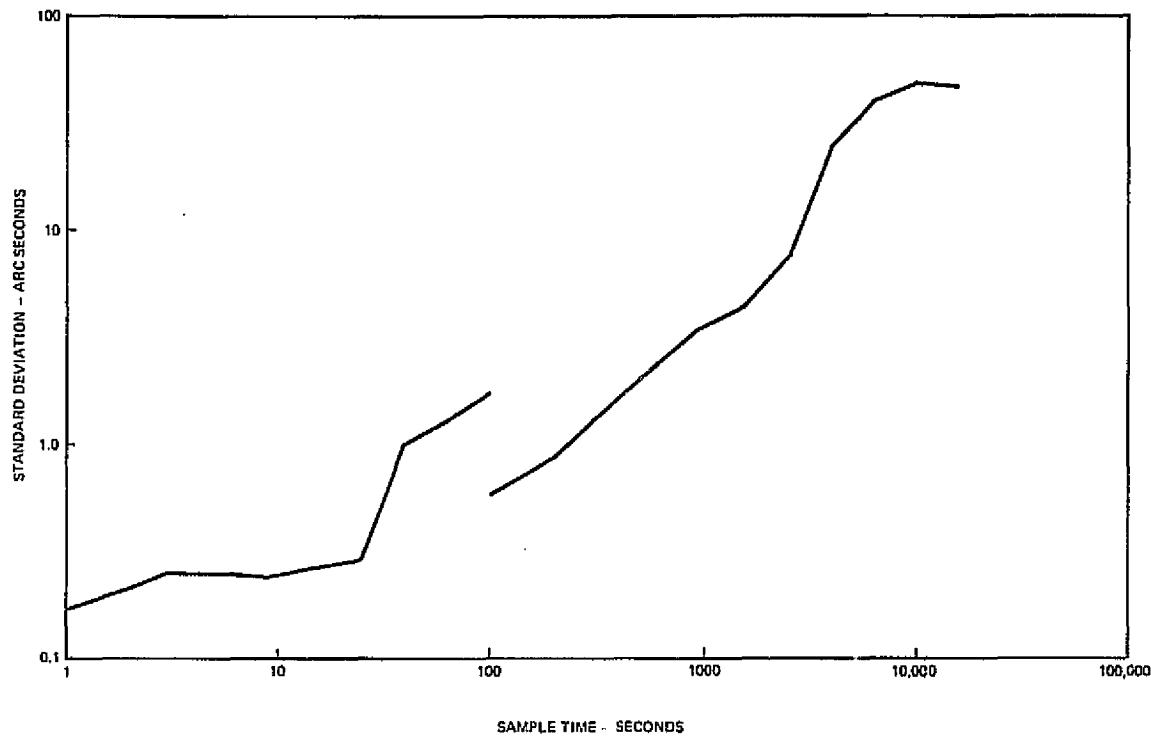


Figure 3-7. Z Gyro Random Drift

The figures indicate that the standard deviations after 20 minutes for the x and y gyros are 0.8 and 1.0 arc seconds, respectively. By coincidence, these values are remarkably close to the value measured for the originally considered Bendix gyros, namely, 0.4 arc seconds.⁽⁴⁾ Also by coincidence, both the x and y gyros and the Bendix gyros have a slope of plus one (log-log plot) for 20 minute and longer samples. These similarities between the malfunctioning IRU x and y gyros and the Bendix gyro confirmed the decision to run the PADS tests with the IRU.

The standard deviation for the z gyro is 4 arc seconds at the 20 minute sample time, and its slope is erratic. While this performance is not ideal, it is close enough to the desired level for the gyro to be used in the system tests. In the evaluations of the system tests results in Sections 9 and 10, the effect of the poor performance of the z gyro on system accuracy is pointed out.

A final comment is appropriate regarding the performance of the x and y gyros. The time plots of gyro drift rate in Appendix C clearly indicate that the dominant error characteristic is a squarewave variation with a

period of approximately 17 hours. It is this characteristic which produces the slope of plus one in Figures 3-5 and 3-6. Although unknown in origin, this error is definitely deterministic in appearance.

3.2 SOFTWARE

The software design is, in general, characterized by achieving desired system performance with the minimum of equation complexity. Throughout the equation development, for example, models derived to compensate for systematic errors in the on-board system are simplified to the level consistent with desired performance. In most cases, for example, this resulted in only first-order terms being retained.

The software is designed to perform executive functions (program control, self-test, system test, etc.), attitude determination, and pointing control in the case of the gimbal star tracker. The attitude determination software derives inertial attitude by integration of the gyro outputs, and employs a Kalman filter for periodic updates to bound the errors. Development of the attitude determination equations required a variety of tradeoffs to determine the appropriate algorithms and design approach. On the other hand, development of equations for transformations, star selection, and gimbal pointing is straightforward, although algebraically complex.

Choice was available for selection of the kinematic variables used to propagate rate through the required numerical integration. Euler symmetric parameters were selected, as opposed to direction cosines, based upon the use of a four, rather than nine, parameter system of equations; also, the periodic renormalization that must be performed to combat computer roundoff error is much simpler. A closed form solution is utilized, under the constraint that the vehicle rate can be assumed constant over each integration interval. The closed form solution tends to inhibit the truncation error that would normally exist in the power series representation. Design analysis was also conducted to establish the integration step size and the effect of computer (roundoff and truncation) errors.

The Kalman filter state vector was limited to six elements (three attitude variables and three gyro biases) to minimize the problem dimensionality while achieving desired performance. Additional states (such as alignment/scale factor parameters in gyros and trackers) were found

not to be justified based upon inherent accuracy/stability and/or relative sensitivity. The extended Kalman filter formulation is utilized where linearization takes place about the previous attitude estimate.

The Kalman filter requires a priori definition of the initial state error covariance matrix, the measurement noise covariance matrix, and the state noise covariance matrix. The initial error covariance matrix reflects the initial uncertainty of the state estimates, and the elements are selected a priori based upon the expected initial attitude uncertainty. There appeared to be little influence of the initial estimate for error covariance, but good design practice indicated selection of values larger than the actual expected initial attitude errors.

State noise arises principally from the gyro random drift, and the elements of the state noise covariance matrix are derived a priori based upon the estimated (measured) gyro noise statistics. The influence of state noise on performance was determined by evaluating the relative error as a function of state noise parameters. A value of the elements of the state noise covariance matrix can be determined which corresponds analytically to the value of gyro noise assuming a white noise gyro model. The tradeoffs indicate that a good design procedure is to utilize the analytically derived values for the state noise covariance matrix which correspond to a conservative estimate of gyro noise.

The elements of the measurement noise covariance matrix are based upon a priori estimates (measurements) of tracker noise. Tradeoffs were made for selection of elements of the measurement noise covariance matrix utilizing a parameter variation study employing various values of tracker noise and measurement noise covariance values. This tradeoff led to the indication that performance can be best achieved through selection of elements of the measurement noise covariance matrix which are, in fact, optimistic.

The PADS software is configured in a modular structure which will permit operational flexibility, capability for growth, and ease of modification. The software makes use of state-of-the-art techniques so far as possible, consistent with the capability of present generation spaceborne computer technology. The software is segmented into modules to be executed under control of the PADS executive according to a preassigned interactive

cycle. Individual program module interfaces have been allocated based upon cycle requirements of the main computation loops.

The following two sections explain those aspects of the PADS software which are peculiar to the strapdown and gimbal systems and their respective star trackers.

3.2.1 Strapdown System Test Associated Software

The sensor information provided by the Inertial Reference Unit (IRU) and the Strapdown Star Tracker (SST) are inputs to the strapdown algorithm, whose purpose is to establish system (spacecraft) attitude and estimate the IRU drift rates. A top level program flow diagram is illustrated in Figure 3-8. Its first task is to read Tape 1 which contains quantitative parameter values associated with the IRU and SST as well as initial estimates (and their statistics) associated with both attitude and gyro drift rates. Table 9-1 in Section 9 specifies a typical list of such inputs. Next a block of IRU and SST data is read into the computer via Tape 4, with successive blocks read thereafter as the data is utilized. For the PADS laboratory setup, the air bearing table angle is also input via Tape 4, as it establishes the reference star line-of-sight to be utilized by the SST. Next the attitude and drift state transition matrices are initialized, and a time tagged slice of sensor data read from the computer memory. If it is not time to terminate the run, the algorithm forms angular rate estimates, applying appropriate drift rate compensations. Next the actual attitude is estimated based upon the previous estimate and the intervening angular rates. The system state can then be printed on the output tape (Tape 2), if desired, and unless there is SST data associated with the present time slice, control returns to a for reading the next time tagged data entry.

When SST data does appear, a countdown begins until that data is actually utilized since the azimuth output of the SST becomes more accurate towards the center of its field of view. Once the data is utilized, the appropriate star is first identified, through use of the air bearing table angle, and the SST output corrected to compensate for nonlinearities off its boresight. The a priori estimate of expected SST output based upon the estimated rather than actual attitude is next formed, and subtracted from

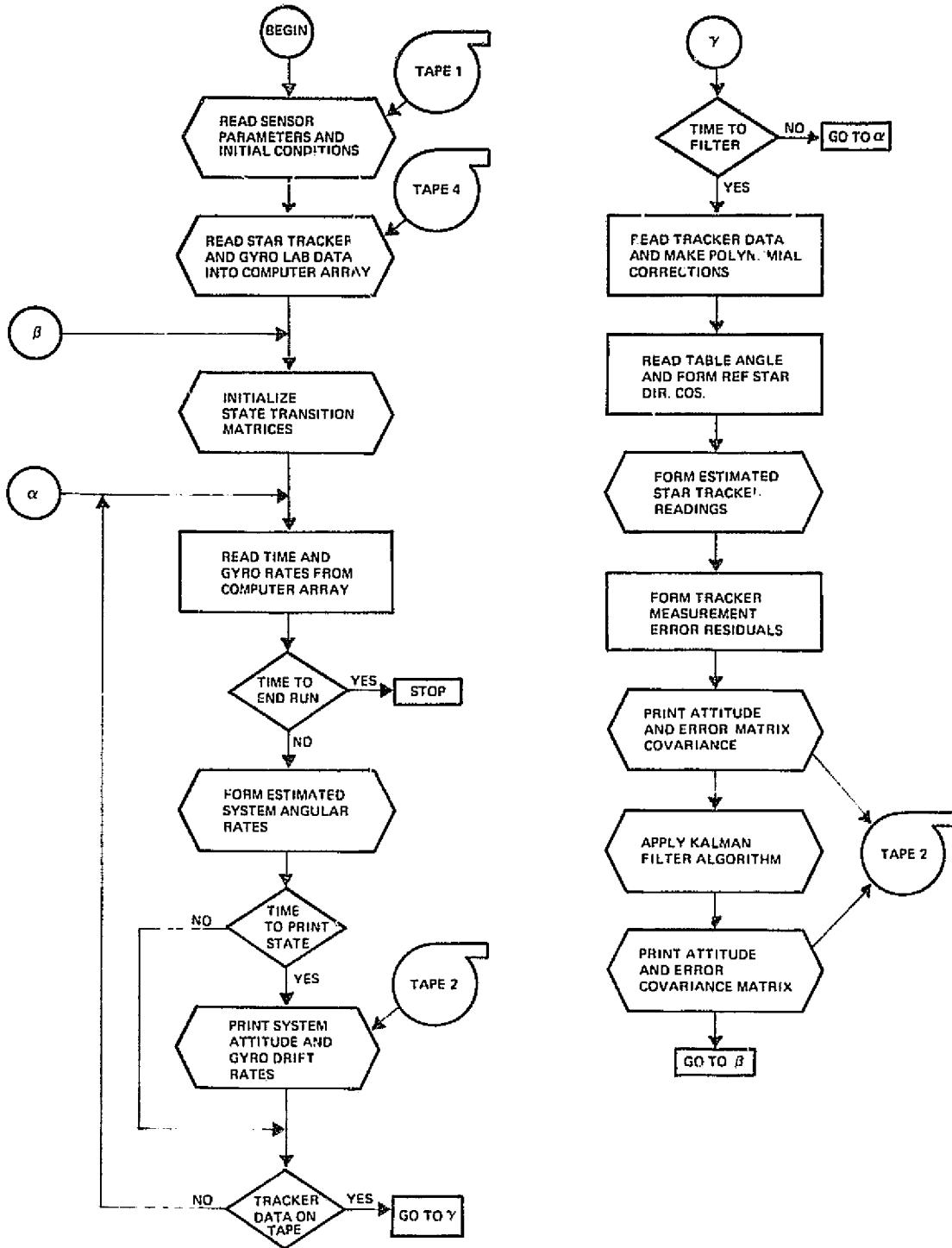


Figure 3-8. PADS Strapdown Software Flow Diagram

the actual readings to establish azimuth and elevation measurement residuals. The Kalman Filter algorithm is then applied resulting in both attitude and RGA drift rate updates. Also derived is an update of the state error covariance matrix, which establishes to what extent the algorithm believes its estimates. Control then returns to β for a new filter cycle. A detailed listing of this computer program appears in Appendix A.

3.2.2 Gimbal System Test Associated Software

The computer program associated with the GST version of PADS is almost identical to that associated with the SST version. The only significant difference involves the replacement of the SST subroutine forming estimated star tracker readings in Figure 3-8 by an equivalent GST subroutine. A detailed listing of the GST version is presented in Appendix B.

4. TEST CONFIGURATION AND ACCURACY

This section describes the laboratory test configuration in relationship to the simulated geosynchronous orbit environment. In addition the potential laboratory error sources are detailed.

4.1 SIMULATED ORBIT CONFIGURATION

The objective of the PADS system tests was to determine the performance capability of a PADS system in geosynchronous orbit through laboratory simulation. Two PADS systems were tested, one using a strapdown star tracker, the other using a single-axis gimbal star tracker. The simulated orbit conditions were the stellar optical stimuli and inertial angular rates which would be experienced on a three-axis stabilized, earth-pointed satellite in geosynchronous orbit.

Before hypothesizing the orbit configuration of both PADS systems, a number of practical test limitations had to be considered. The most important limitation was that only one strapdown star tracker could be developed under the scope of the program. Since practically no geometric leverage is obtained about the boresight of a 1° by 1° field of view, this meant that system performance would be achieved only about the two axes normal to the boresight: in essence, a two-axis test for the strapdown system.

Another limitation was the fact that it was technically impossible within the scope of the program to accurately simulate bright object interference to the performance of the star trackers. In view of this, the assumed orientations of the tracker fields of view in orbit were picked with the objective to make sensor errors as nearly as possible one-to-one with system errors.

With these considerations in mind the simulated orbit configurations which were arrived at are shown in Figure 4-1. It is seen that the strapdown system is a two-axis system consisting of one narrow field of view and two gyro input axes orthogonal to the field and to each other. For maximum star availability on the assumed uniformly distributed celestial sphere, the field of view points at the celestial equator. On the other hand, the gimbal system is a three-axis system since the 90 degree sweep of the tracker field of view does give adequate geometric leverage for three-axis tracker information, supplemented by the three orthogonal gyro axes. The center of the sweep is also pointed to the celestial equator for maximum star availability.

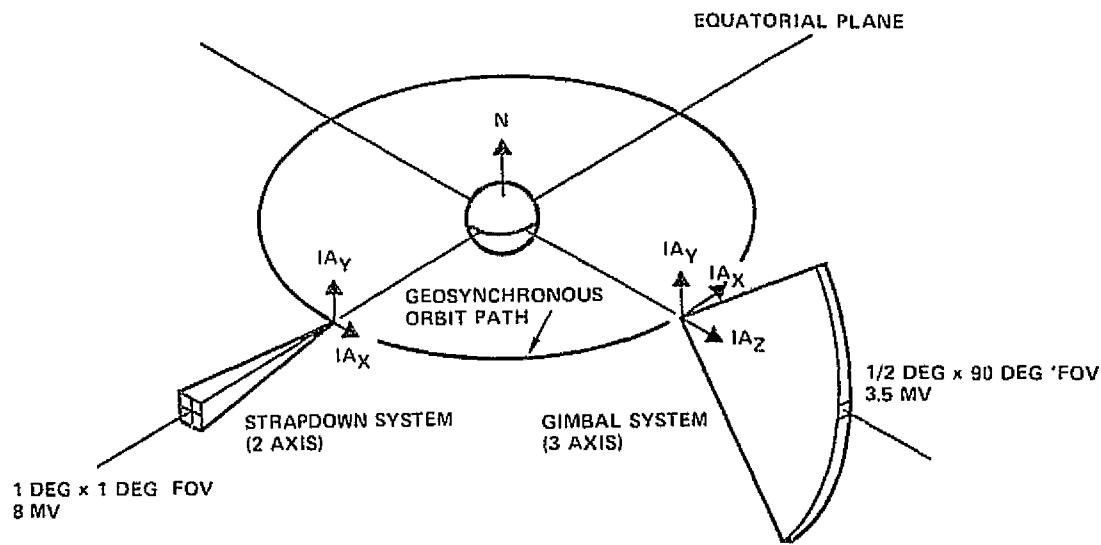


Figure 4-1. Simulated Orbit Configuration

The driving function for star update frequency is the random drift of the gyros. For the class of gyro considered on PADS a nominal update period of 20 minutes has been chosen in order to result in a total system accuracy of 0.001 degree. Using the equations developed in Volume I, Section 2.2, a 20 minute period in the case of the strapdown star tracker gives a probability of at least one star occurring in the field of view of:

$$p = 0.9963$$

For the gimbal star tracker a 20 minute period gives a probability of

$$p = 0.9736$$

To make the probability for the gimbal tracker equal to that of the strapdown tracker the update period must be extended to 32 minutes.

For the PADS testing the decision was made to make the star update period 20 minutes for both strapdown and gimbal cases. This is equivalent to acquiring a star every 5 degrees of right ascension in geosynchronous orbit. In the analysis of the test data a parametric analysis of the effect of update period was obtained by skipping updates. In this manner 20, 40, and 60 minute update periods were obtained. This approach was taken since

it simplified test procedures and avoided longer test runs in the case of the gimbal system. Comparison between the two systems was made on the basis of the parametric analyses.

Three different star declinations were used in the case of either system. For the strapdown system the purpose of multiple declinations was to exercise the accuracy of the tracker at more than one place in the field of view. The three declinations were:

- Star 1: 911.6 arc sec (0.3^0)
- Star 2: 0.0 arc sec (0.0^0)
- Star 3: -326.0 arc sec (-0.1^0)

For the gimbal system the motivation for three declinations was to obtain three-axis star tracker information as well as to exercise the accuracy of the gimbal readout. Here the three declinations were:

- Star 1: 53814.9 arc sec (14.9^0)
- Star 2: -14564.8 arc sec (-4.0^0)
- Star 3: -82958.0 arc sec (-23.0^0)

4.2 LABORATORY TEST CONFIGURATION

The key distinguishing feature of the laboratory test configurations for both the strapdown and gimbal system tests is that a ground-fixed test is implemented. The earth itself is used to simulate the inertial motion of an earth-pointed geosynchronous satellite. This is accomplished by mounting the PADS sensors stationary to the laboratory floor, which itself is a seismic pad isolated from building vibrations. The stellar optical stimuli are simulated by sweeping collimating star beams past the stationary PADS sensors. Ideally, the star beams, which are revolving at earth rate relative to the laboratory, are stationary in inertial coordinates since their rotation relative to the laboratory cancels the rotation of the laboratory, or the earth, relative to inertial space. In practice, since it was more practical to have the rotation axis of the stars vertical in the laboratory, and since the laboratory location was in Manhattan Beach, California, the star line-of-sights actually were rotating in inertial space. However, since the stars were revolved at earth rate

relative to the star trackers, the test configuration still satisfied the objective of the tests, namely, to evaluate the performance of the PADS systems.

Isometric representations of the strapdown and gimbal configurations are shown in Figures 4-2 and 4-3, respectively. Table 5-1 in Section 5 identifies the numbered equipment. Photographs of the actual configurations are shown in Figures 4-4 through 4-17. Figures 4-4 through 4-10 show details of the star stimulus of the strapdown star tracker. Stimulus of the gimbal star tracker is shown in Figures 4-11 through 4-16. The inertial reference assembly is shown in Figure 4-17.

The ground-fixed test provided two major advantages over the conventional approach of rotating the PADS on a rate table in the center of a room, and placing multiple star sources around the room which point at the rotating PADS. The first advantage is that the ground-fixed approach is compatible with the parallel beam star stimulus technique described in the following section. This technique is essential to providing laboratory instrumentation knowledge of star locations with one arc second accuracy. The technique is not compatible with the rate table and multiple stars approach. The second advantage is that the artificial subtraction of earth rate from the gyro outputs is not necessary in the ground-fixed approach. In fact, it becomes technically dubious in the rate table approach since a vector of the same magnitude as that produced by the rate table must be subtracted from the gyro outputs.

In the ground-fixed test approach, the PADS axes are identical to the laboratory axes. Both are physically defined by optical surfaces on the star trackers. The strapdown star tracker uses the normals to two faces of an optical cube to define the axes. The gimbal star tracker uses an orthogonal set of axes whose orientation is defined relative to three mirror surfaces on the tracker base. Star orientation relative to the laboratory (and PADS) axes is measured by laboratory instrumentation.

The PADS output is a continuous estimate throughout the length of the test run of the attitude of the PADS axes relative to their inertial attitude at the start of the test run. For performance evaluation this output is compared to the continuous inertial attitude of the physically defined

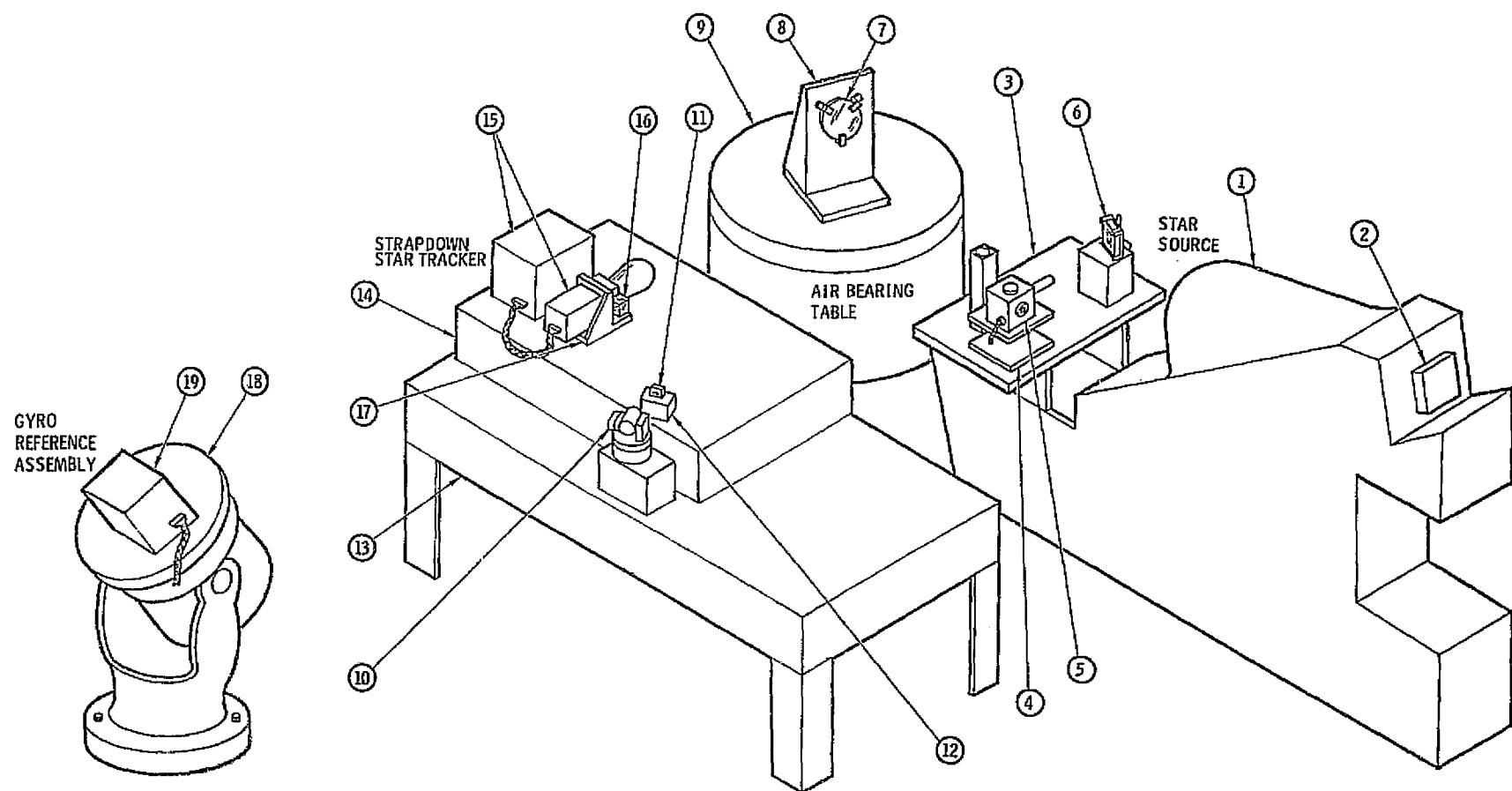


Figure 4-2. Strapdown Test Configuration

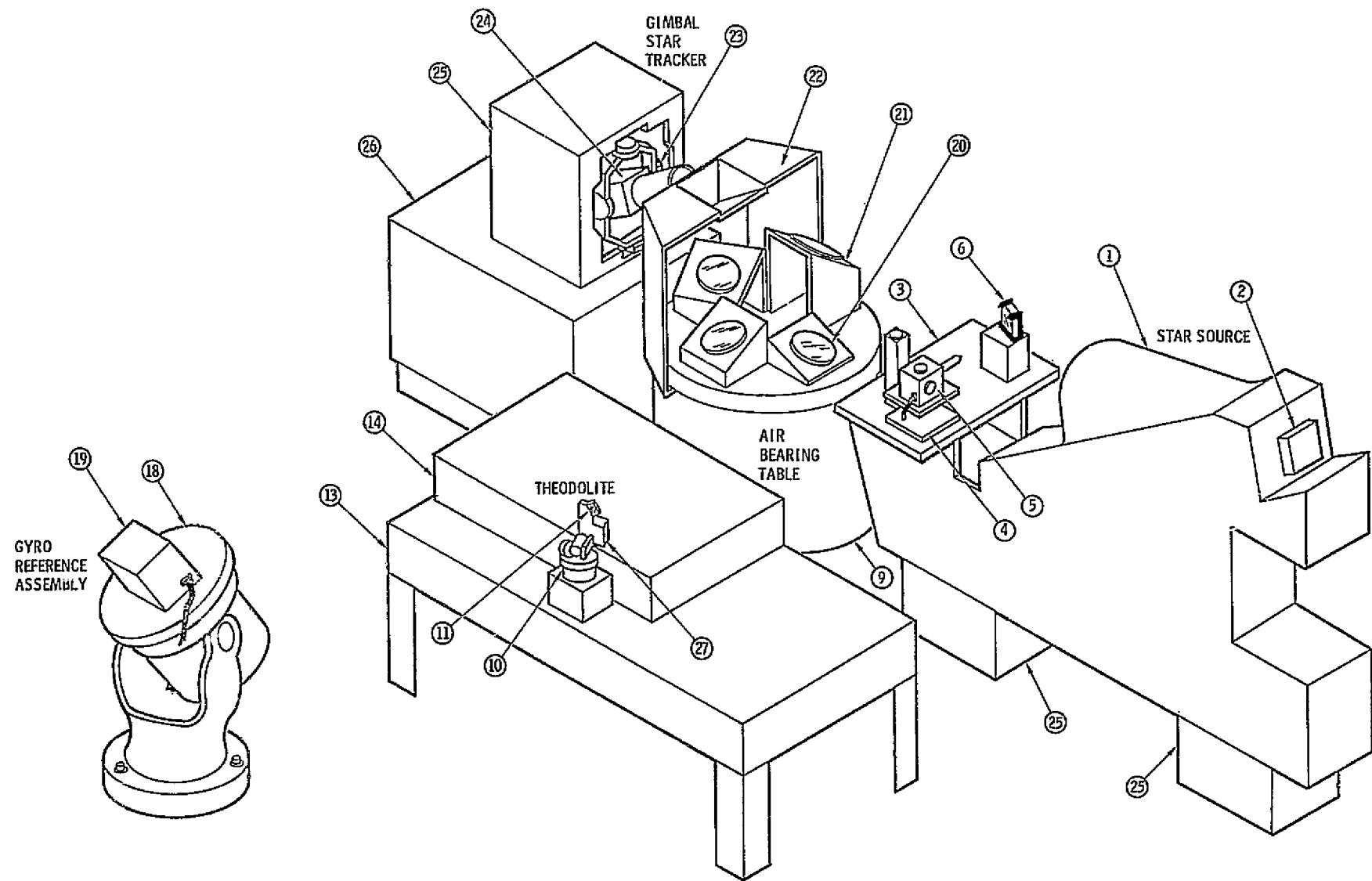


Figure 4-3. Gimbal Test Configuration

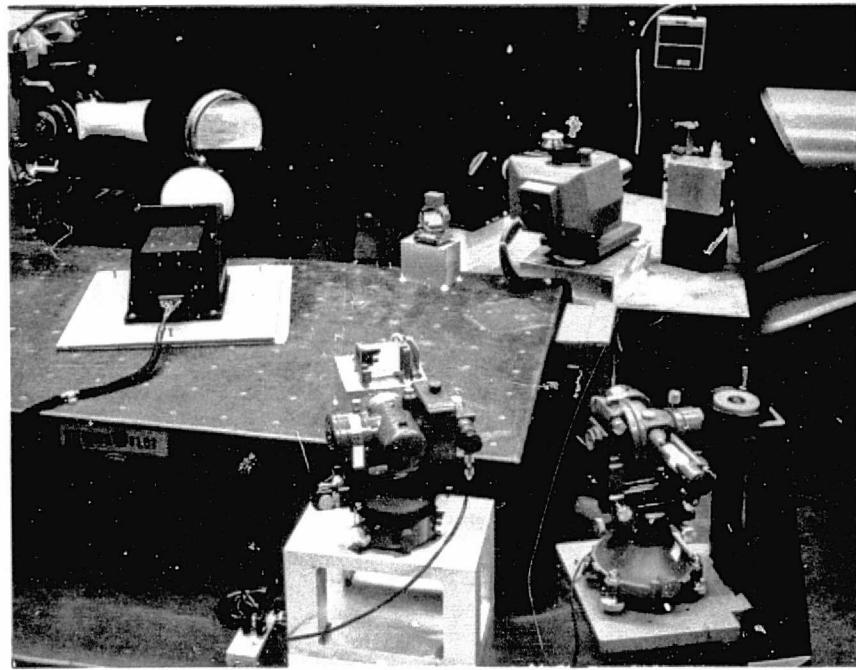


Figure 4-4. View of Strapdown Configuration



Figure 4-5. View of Strapdown Configuration From Back of Theodolite

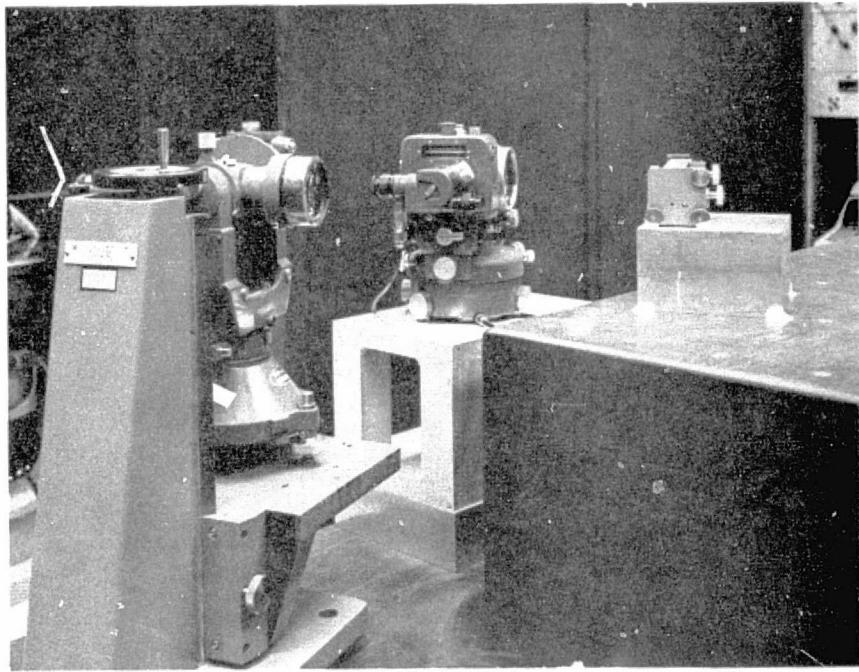


Figure 4-6. Front View of Theodolite

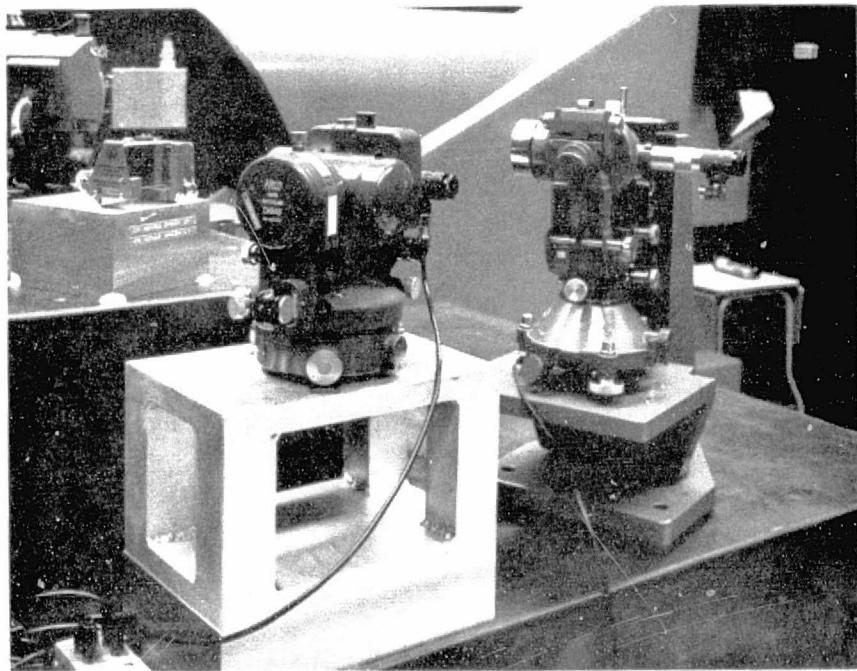


Figure 4-7. Back View of Theodolite

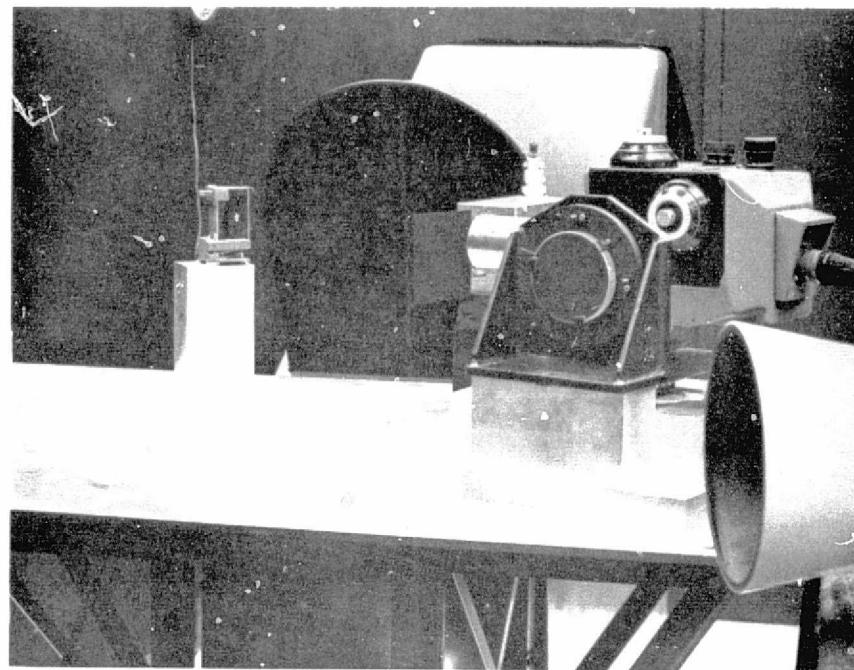


Figure 4-8. View of Automatic Autocollimator From Right of Star Source

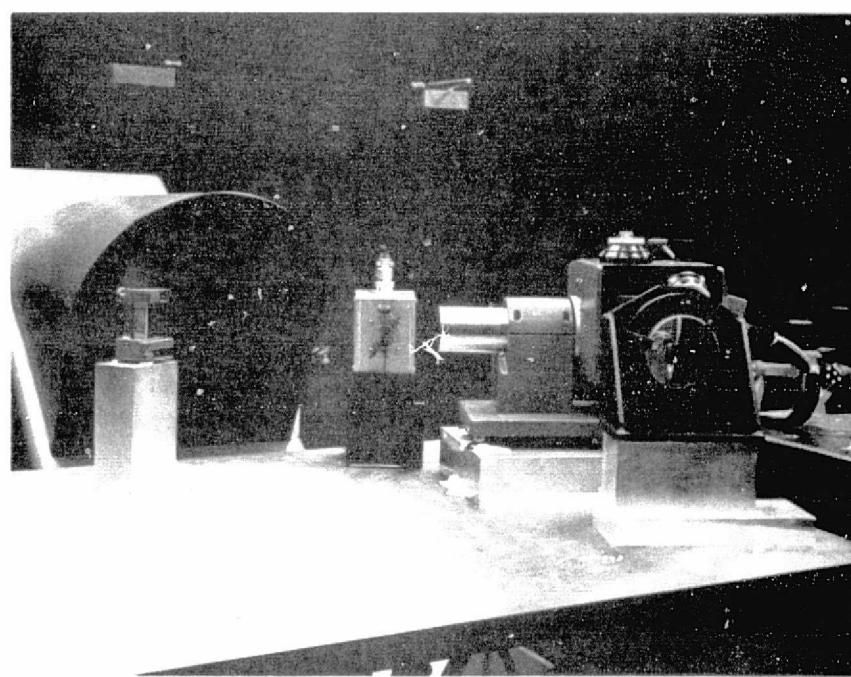


Figure 4-9. View of Automatic Autocollimator From Left of Star Source

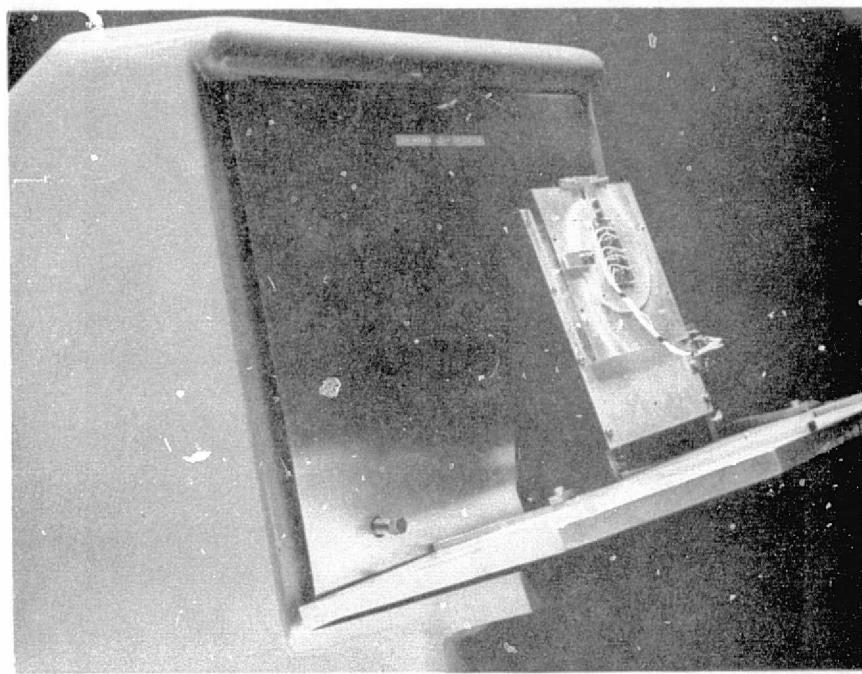


Figure 4-10. LED Assembly on Star Source

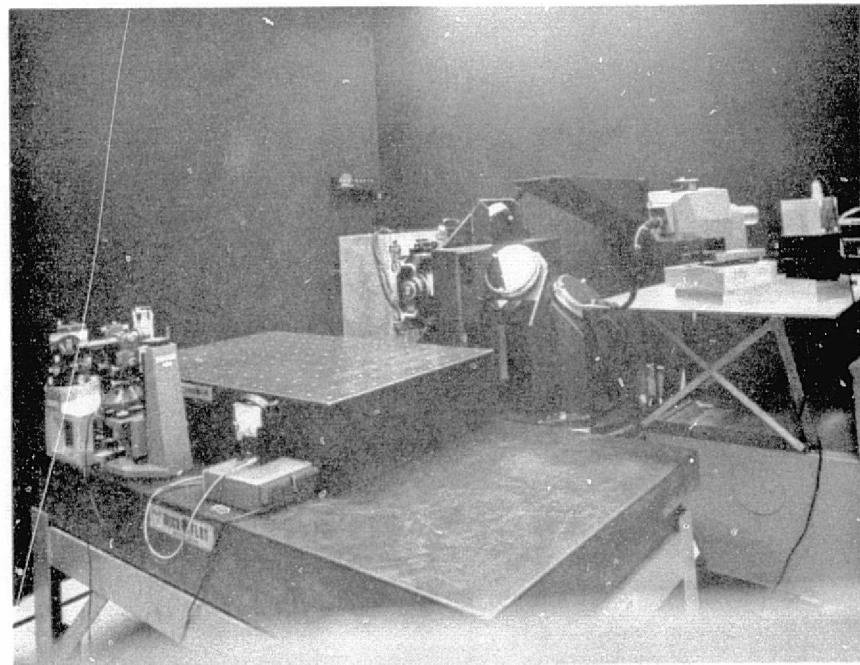


Figure 4-11. View of Gimbal Configuration

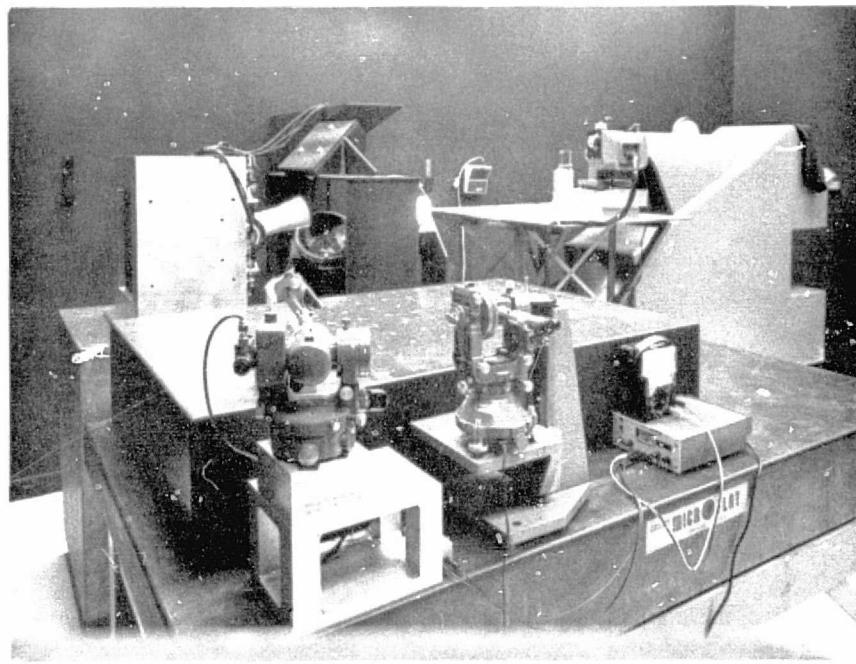


Figure 4-12. View of Gimbal Configuration From Back of Theodolite

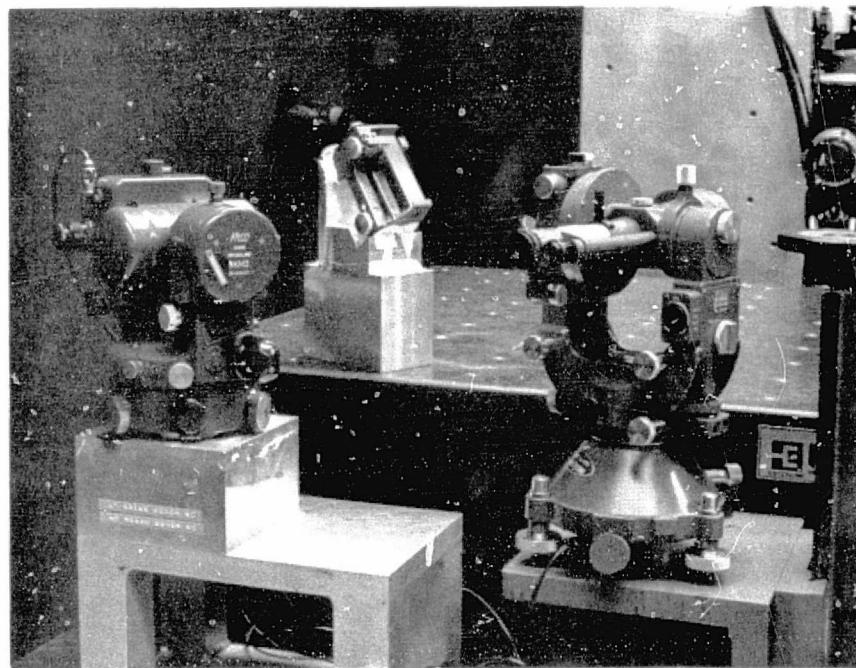


Figure 4-13. Side View of Theodolite and Double-Sided Mirror

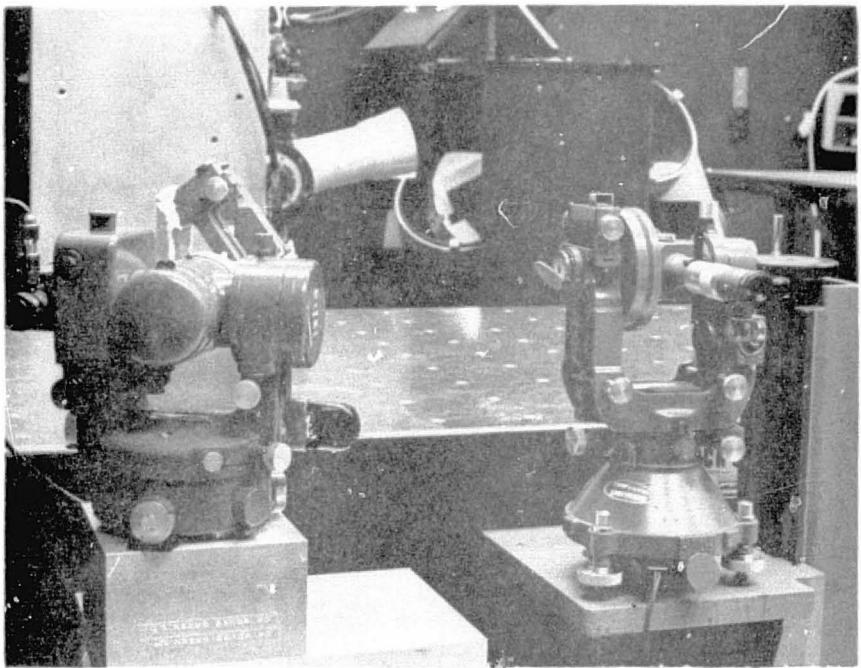


Figure 4-14. Theodolite View of Mirror Assembly in Reference Position

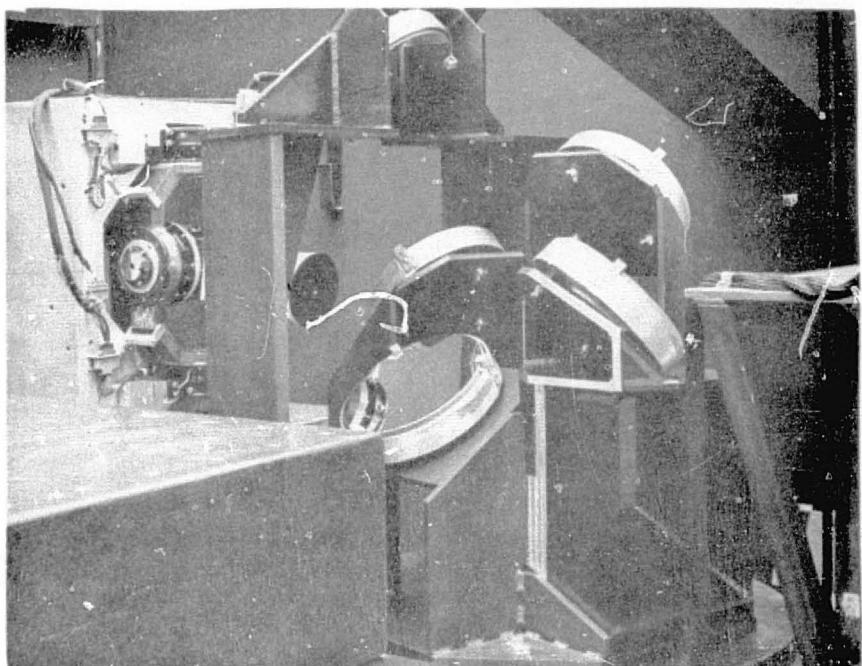


Figure 4-15. Stationary and Rotating Mirrors in Star 2 Position

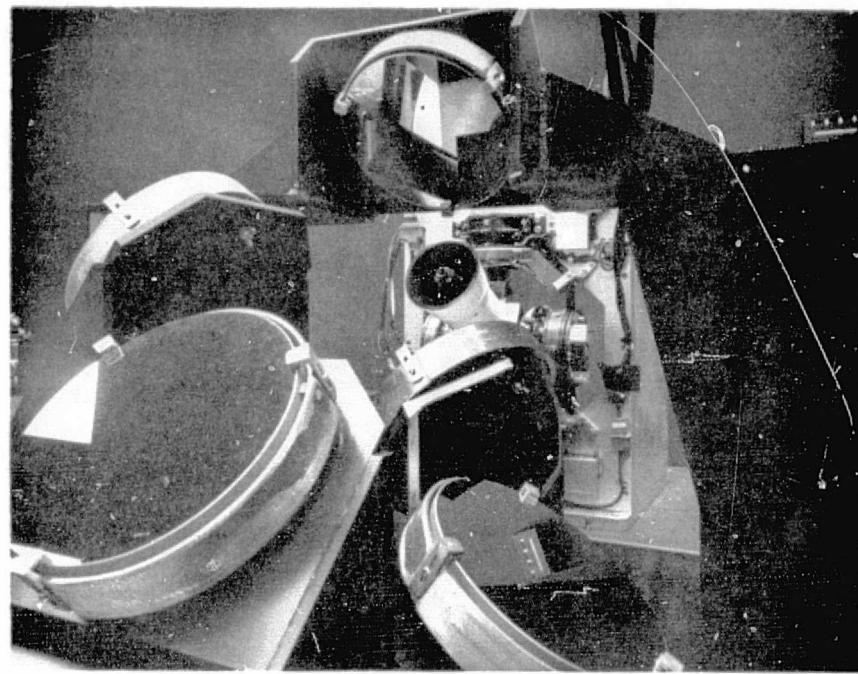


Figure 4-16. Stationary and Rotating Mirrors in Reference Position

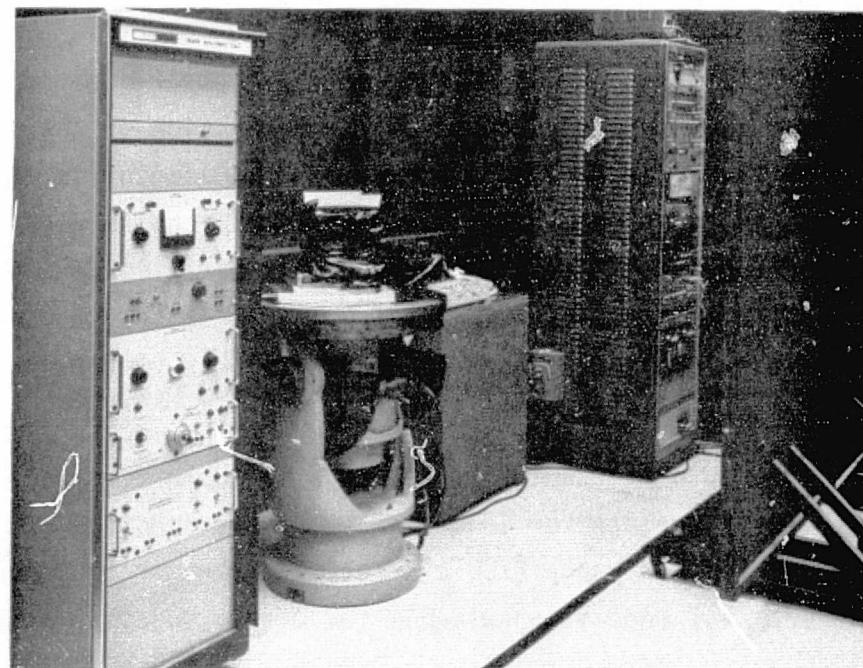


Figure 4-17. Inertial Reference Unit

PADS axes. This attitude is derived from the inertial attitude of the laboratory axes at the start of the test and from knowledge of the rate of the earth's rotation. The star orientation is measured relative to the laboratory axes. It is important that the star orientation in laboratory axes be known very accurately using laboratory instrumentation. An error in knowledge of the star position will result directly in an error in the performance evaluation of the PADS.

4.3 PARALLEL BEAM STAR STIMULUS TECHNIQUE

The key test configuration accuracy requirement is to know the orientation of the star line-of-sight relative to the laboratory axes, which in this case are also the PADS axes. Since the PADS performance requirement is 3.6 arc seconds per axes, knowledge of the star orientation must be significantly better than this value. By using a parallel beam star stimulus technique an accuracy approaching one arc second was obtained.

The parallel beam technique is perhaps best illustrated by the top view of the strapdown system test configuration shown in Figure 4-18. Functionally, the performance of a star transit (defined as a sweep of a star through the field of view of the tracker) is straightforward. The collimated star beam from the star source is reflected off the rotating mirror mounted on top of the air bearing table. The table is turned at half earth rate so that the reflected star beam sweeps past the star tracker at earth rate. In order to measure where the star beam is relative to the PADS axes, i.e., the optical cube on the right side of the star tracker, the collimated beam from an automatic autocollimator is transmitted parallel to the star beam. The normal to the front face of the cube is the defined boresight axis of the tracker. When the star beam (Star 2) is coincident with the boresight axis, the autocollimator beam will be normal to the front face, and the horizontal and vertical output of the two-axis autocollimator will be zero.

This use of the automatic autocollimator is suitable for a static indication of the star orientation in a small region around the boresight axis. However, its limited range (± 50 arc sec) and dynamic response (0.13 arc sec per arc sec/sec) make it unsuitable for a star sweeping through

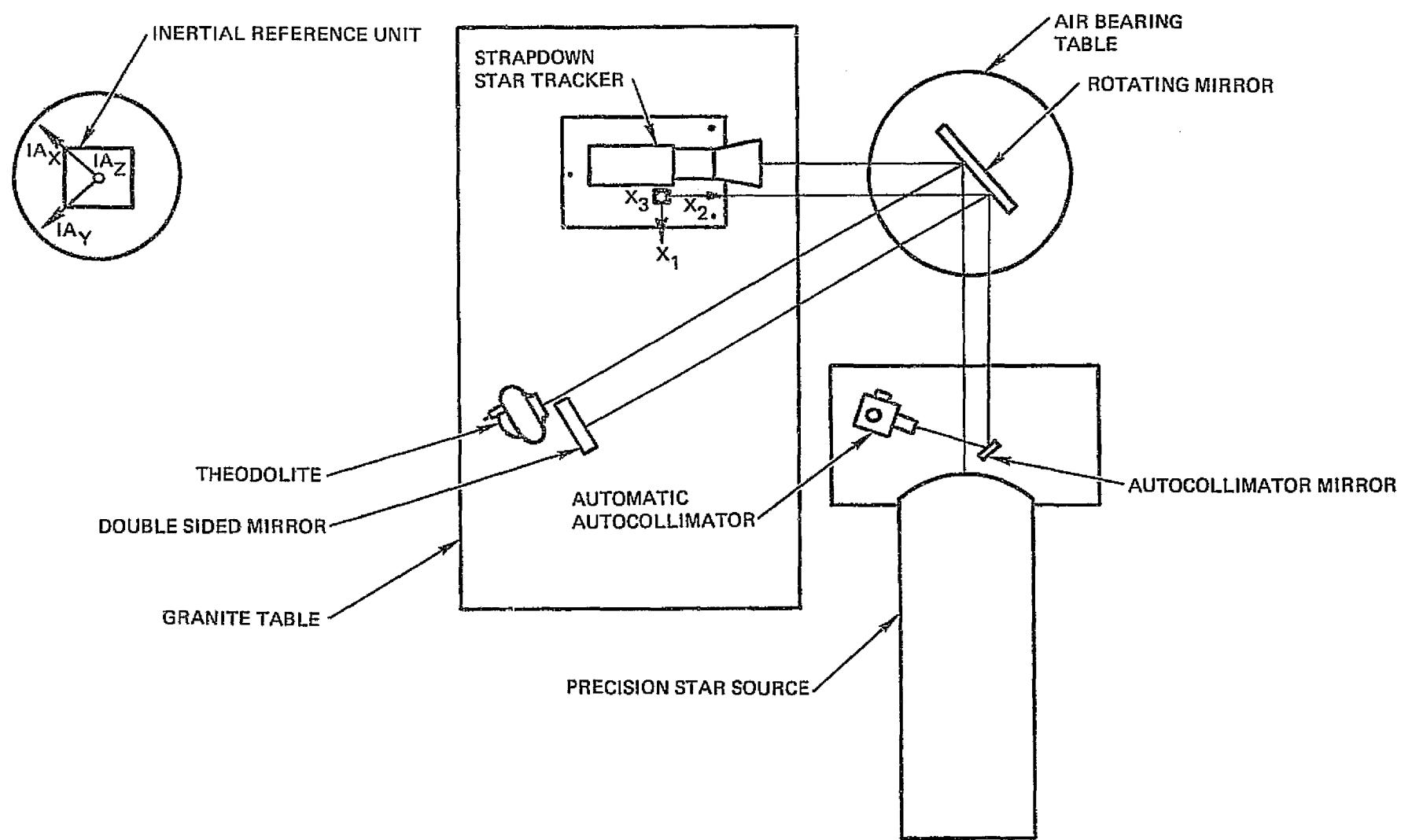


Figure 4-18. Strapdown Star Test Configuration

the 1° field of view at earth rate during a star transit. For this case the air bearing table readout is used. The zero reference for the readout is obtained by making a static table reading at the boresight position indicated by the automatic autocollimator.

So far the discourse has been limited to measuring the location of the center star (Star 2) relative to the PADS axes. By independently measuring the relative locations of the other two stars to the center star, their locations relative to the PADS axes can also be determined by the parallel beam technique. The independent measurements were made with a theodolite. The gravity vector was used as a reference for rotations about the boresight axis.

The key to the successful implementation of the parallel beam method is the ability to recalibrate as frequently as necessary the parallelism between the collimated center star and autocollimator beams. This is facilitated by use of the theodolite and double-sided mirror shown in Figure 4-18. The double-sided mirror is positioned half way in front of the aperture of the theodolite. The backside mirror is positioned perpendicular to the theodolite boresight by using the autocollimator feature of the theodolite. Since the frontside mirror is parallel to the backside mirror, the normal to the frontside is then parallel to the telescope boresight of the theodolite. Both can now be used to calibrate the parallelism between the two collimated beams. The air bearing table is rotated until the star beam is along the boresight of the theodolite. When this condition exists, the automatic autocollimator will adjust its beam normal to the frontside mirror. Any deviations from zero of the autocollimator horizontal and vertical outputs represent its null bias errors. The utility of this recalibration method is that it can be performed at any time during a test period.

The operational procedure which was developed during the test phase was to recalibrate in two stages. The strapdown or gimbal test consisted of four runs, four hours or longer in duration, which were performed over a ten day period. Since the star source beam would drift relative to the theodolite up to a couple of arc seconds per day, and since the air bearing table readout zero position would also shift from turn-on to turn-on, the

two collimated beams were realigned parallel at the start of each run. This was accomplished by driving the table to the reference (theodolite) position, adjusting the theodolite so that the center star was on boresight, adjusting the double-sided mirror face normal to the boresight, and then adjusting the autocollimator mirror to give zero horizontal and vertical output for the automatic autocollimator. The alignment of the star and double-sided mirror to the boresight was also checked at the end of each run to verify that no detectable misalignment occurred. This was found to always be the case. During the four or five hour test run, however, the automatic autocollimator would drift up to three arc seconds. Therefore, before the start of each star transit (20 minutes apart), the table would be driven to the reference position and the autocollimator zero position recalibrated.

By using this operational procedure the only temporal stability requirements necessary for the entire test configuration were:

- 1) A four or five hour stability of the star source relative to the theodolite
- 2) Approximately a five minute stability of the autocollimator beam relative to the star beam. Stabilities better than one arc second were easily obtained by using a thermally passive star source and the Davidson Model 696 autocollimator.

4.4 LABORATORY ERROR SOURCES

The PADS system axes are defined by the optical cube. The computer axes are an analytical entity and represent the computed estimate of the orientation of the system axes relative to a set of reference axes. The computed estimate is derived from gyro and star tracker information. The reference axes are defined to be the inertial attitude of the system axes at the start of the test period.

The test purpose was to compare the attitude of the computer axes with that of the system axes, where both are expressed relative to the reference axes. The system attitude error is indicated by

$$\hat{A}_{XZ} \cdot A_{XZ}^T$$

where \hat{A}_{XZ} and A_{XZ} are the direction cosine matrices of the computer and system axes, respectively, relative to the reference axes.

The matrix \hat{A}_{XZ} is computed from the initial estimate of its orientation relative to the reference axes (which are also the system axes at test start), and from the output signals of the gyros and the star trackers. The matrix A_{XZ} is computed from knowledge of the initial orientation of the system axes at test start relative to the earth rate vector, and from time.

Figure 4-19 provides a useful representation of the coordinate axes and star vectors involved. Misalignment between computer and system axes is indicated at a star update time as the difference between:

- 1) Where the star should be in computer axes
- 2) Where the star is actually measured in system axes by the star sensor.

Where the star should be in computer axes is calculated as a function of:

- 1) The direction cosine matrix (or quaternion) relating the computer axes to the reference axes
- 2) A star catalog which describes where the star is in the reference axes.

This difference is then used (via a Kalman filter) to correct the direction cosine matrix. In between star update times, the incremental attitude change measured by the gyros is used to change the direction cosine matrix.

In the PADS Laboratory test configuration the star catalog information is partly measured and partly analytical. The autocollimator directly measures where the star is in system axes, but the orientation of the system axes to the reference axes is an analytical relationship established by definition and the laboratory measurement of time.

Thus, laboratory measurement accuracies can be divided into two links:

- 1) The attitude of the system axes relative to reference axes
- 2) Star position relative to system axes.

The following sections describe the errors associated with both.

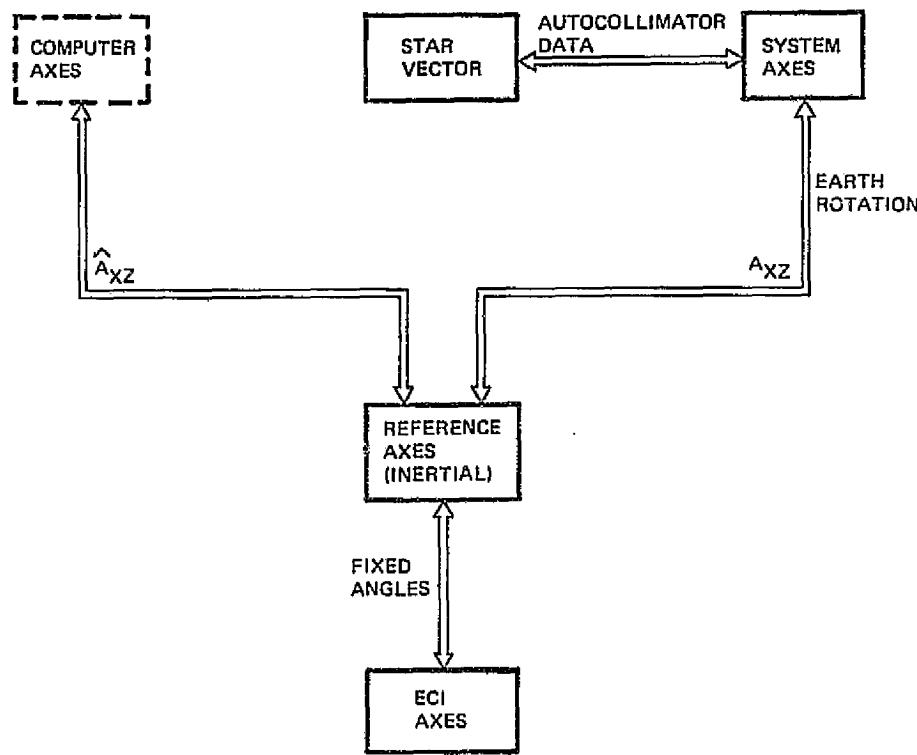


Figure 4-19. PADS Coordinate Systems

4.4.1 PADS System Attitude Uncertainties

Consider first an error in the matrix A_{XZ} at the start of the test due, for example, to incorrect knowledge of the latitude of the laboratory. This error will not evidence at a star update since A_{XZ} is used in both those quantities which are differenced and input to the Kalman filter. The error will cancel itself. On the other hand, it will appear initially in the gyro outputs. But, after a number of star updates, the filter will attribute the error to a gyro bias and thereafter compensate for it. Since the PADS system experiences a constant rate vector (earth rate) throughout the test, this error is indistinguishable from actual gyro bias error, scale factor errors, or input axis misalignments. However, separately identifying these error sources was not considered essential to the test objective of determining the PADS performance capability.

Seismic disturbances of the laboratory during a four or five hour test run will directly affect the laboratory evaluation of PADS. These disturbances will evidence as a random drift component in the gyro outputs.

However, from the measurements of the OAO/IRU performance both at GSFC and TRW it is clear that the gyro errors will completely predominate over possible seismic motions of the isolated laboratory floor.

Summarizing, neither static nor dynamic errors in describing the orientation of the PADS axes relative to inertial space significantly affect the laboratory evaluation of the PADS accuracy.

4.4.2 Star Position Measurement Errors

Determination of star position relative to the PADS system axes represents the major laboratory measurement error affecting the laboratory evaluation of the PADS accuracy. Since the PADS accuracy goal is 3.6 arc sec (1σ), the goal for this error source arbitrarily was selected to be 0.36 arc seconds (1σ), or 1.1 arc seconds (3σ). The ground rule was established that no attempt would be made to improve the measured PADS accuracy results by subtracting out either a statistical or deterministic measure of the laboratory errors.

Accuracy in knowledge of star line-of-sight position relative to the PADS axes is limited by three types of errors:

- 1) Absolute Errors. This term refers to systematic error sources which are present for all test runs.
- 2) Repeatability Errors. These are errors due to the realignment of the parallel beams prior to each test run. These errors are random from run to run, but constant for any one run.
- 3) Random Errors. These errors are random for any sequence of star measurements made either during a star transit or from transit to transit.

A further distinction which has been made is whether or not an error affects all three stars in the same manner, or if it is uncorrelated from one star to the next.

The error sources for the PADS test configurations are shown in Table 4-1. Since the purpose of the test program was to determine the performance capability of PADS, the systematic error of 3.3 arc seconds for all three stars, during all test runs, was not considered relevant. This error will not show up in the test results since both star trackers

Table 4-1. Star Measurement Errors

Error Source	Strapdown System Error - Arc Sec		Gimbal System Error - Arc Sec	
	All Stars (3 σ)	Star to Star (3 σ)	All Stars (3 σ)	Star to Star (3 σ)
1. Absolute Errors - All Runs				
Star Position Measurement	0.0	0.6	0.0	1.2
Star Beam Collimation	0.0	0.0	0.0	0.0
Star Intensity Uniformity	3.0	3.0	3.0	0.0
Double-Sided Mirror Nonparallelism	1.0	0.0	1.0	0.0
Theodolite Boresight Alignments	0.7	0.0	0.7	0.0
Theodolite Spherical Aberrations	0.0	0.0	0.0	0.0
Theodolite Circle Accuracy	0.0	0.6	0.0	0.6
Theodolite Level Accuracy	0.0	0.0	-	-
Table Readout Accuracy	0.3	0.0	-	-
RSS	<u>3.3</u> ¹	<u>3.1</u> ²	<u>3.3</u> ¹	<u>1.3</u>
2. Repeatability - Run-to-Run				
Theodolite FOV Precision	0.6	0.0	0.6	0.0
3. Random - During Run				
Autocollimator Noise	-	0.2	-	0.2
Autocollimator Drift	-	0.0	-	0.0
Autocollimator Scale Factor Error	-	0.3	-	0.3
Table Readout Quantization	-	0.6	-	0.5
RSS		<u>0.7</u>		<u>0.6</u>

1. Not relevant to PADS test.

2. Eliminated by field of view calibration and compensation.

are initially aligned using the same test configuration. It would suffice, however, if the same PADS hardware, aligned using the laboratory configuration, were operated in orbit. The star to star absolute error of 3.1 arc seconds for the strapdown system also was eliminated by performing a strapdown star tracker field of view calibration and compensation using the same test configuration. As described in Volume I, Section 7, this was necessitated by inconsistencies discovered in the initial calibration data for the strapdown star tracker. All the remainder of the errors do affect the PADS performance results, and in combination (RSS) give 0.9 arc seconds (3σ) for the strapdown system and 1.6 arc seconds (3σ) for the gimbal system.

The most significant fact regarding the errors listed in Table 4-1 is that no significant error source due to temporal instabilities or drifts is present. As previously mentioned, this is a result of use of the parallel beam technique.

The following sections describe in detail the error sources listed in Table 4-1.

4.4.2.1 Star Source

The primary requirement for the star source was that it be stable to within an arc second throughout a four or five hour test run. This requirement was met by constructing a thermally passive source consisting of a Davidson (Model D-278) reflective bench and low power LED point sources. Since every part of the source was essentially at room temperature, no thermal deformations were possible.

The optics consist of a parabolic primary mirror with a focal length of 272 cm, and a flat secondary mirror. The aperture diameter is 40.6 cm with a center obscuration of less than 5.1 cm diameter.

The LED point sources are mounted in an aluminum plate which has a glass photographic plate bonded to its front side. The star images are formed by the photographic plate. Figure 4-20 illustrates the angular size and spacing of the three stars used in the strapdown system test. The vertical reference in the figure is the gravity vector with the plate in position for the strapdown test, and the stars as seen looking into the star source. The measurements were made with the Kern DKM3 theodolite.

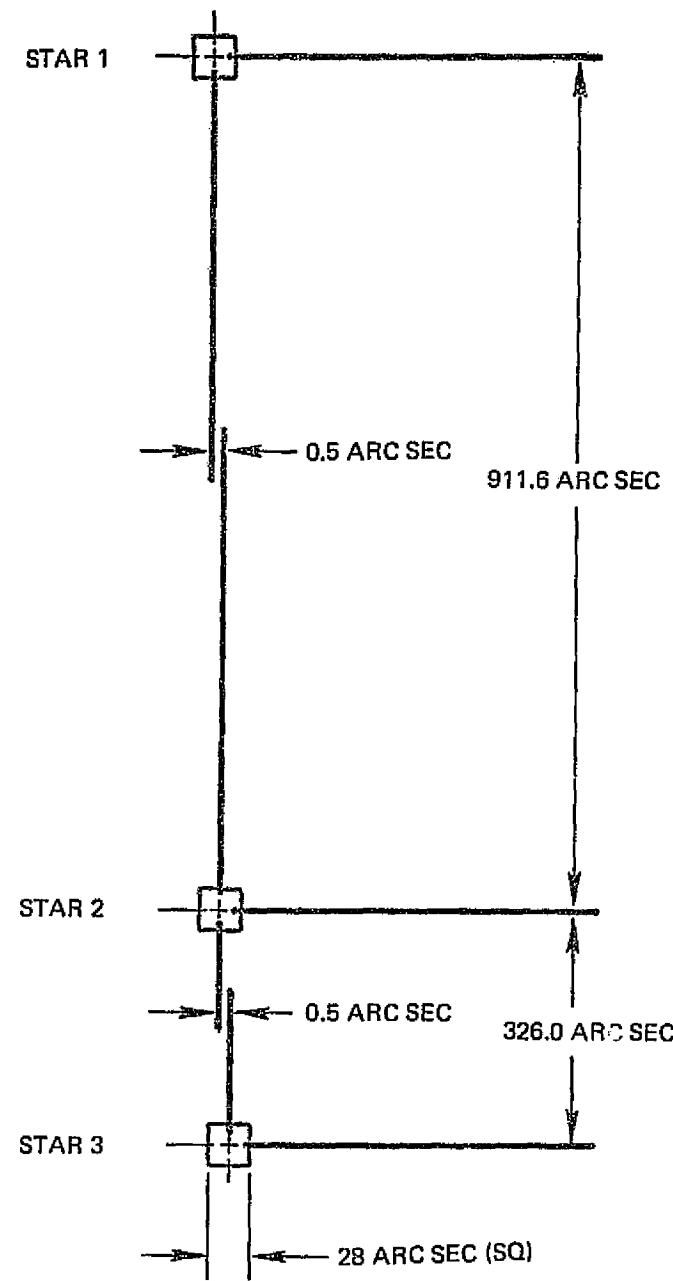


Figure 4-20. Angular Measurements of the LED Sources

The theodolite was placed in the same position in the collimated beam occupied by the strapdown star tracker. Each angle is the average of three measurements. Of the six angles the maximum standard deviation about the mean is 0.4 arc second; the peak deviation from the mean is 0.9 arc second. Using the maximum standard deviation, the standard deviation of the mean is 0.2 arc second.

For the gimbal test the center star was used together with a number of mirrors to produce the three different star elevations. A stationary mirror and three rotating mirrors were used to deflect the star beam. The mirrors were adjusted so that the star beam was normal to each of the three reference mirrors on the side of the gimbal star tracker base. This was accomplished by first adjusting the star beam parallel to the automatic autocollimator beam, and then adjusting the rotating mirrors so that the autocollimator beam was normal to each reference mirror face. Immediately following this adjustment, the tracker was removed, the theodolite inserted in its position, and the three star angles were measured. Figure 4-21 illustrates the measured angles. The reference axes are the gravity vector and an arbitrary azimuth. Each angle is the average of three measurements. The maximum standard deviation of the six angles is 0.7 arc second; the peak deviation from the mean is 1.0 arc second. Using the maximum standard deviation, the standard deviation of the mean is 0.4 arc second. The increase in measurement error over that obtained for the LED sources was due to two effects:

- 1) A drift trend in the measurements, probably due to motion of the deflection mirrors
- 2) Less precision in centering the theodolite crosshairs over the square star which was tilted for the gimbal tests.

The stars were made square to improve the repeatability of the field of view positioning of the theodolite. Figure 4-22 shows the vertical crosshairs of the DKM3 positioned over a star. The star was made large enough so that a strip approximately 2 arc seconds wide appeared outside of the crosshairs. The operator would position the instrument so that both strips appeared equal in width. A 0.5 arc second error in centering would produce an easily discernable 60 percent difference in strip widths.

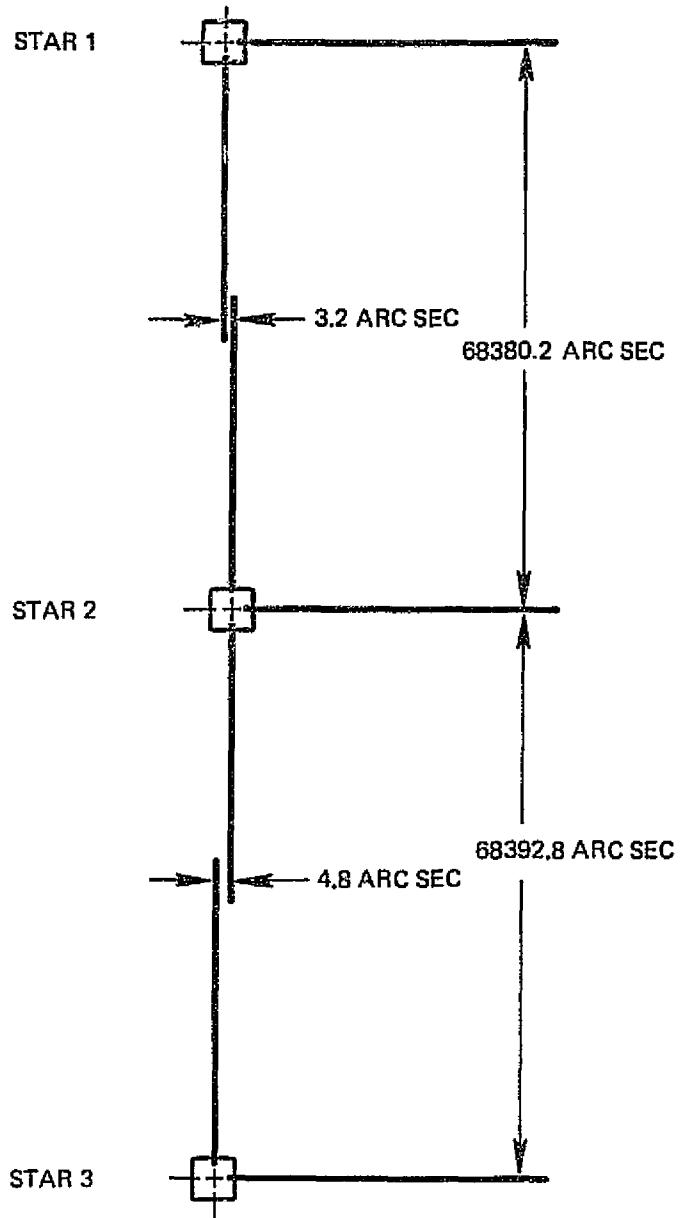


Figure 4-21. Angular Measurements of the Gimbal Star Sources

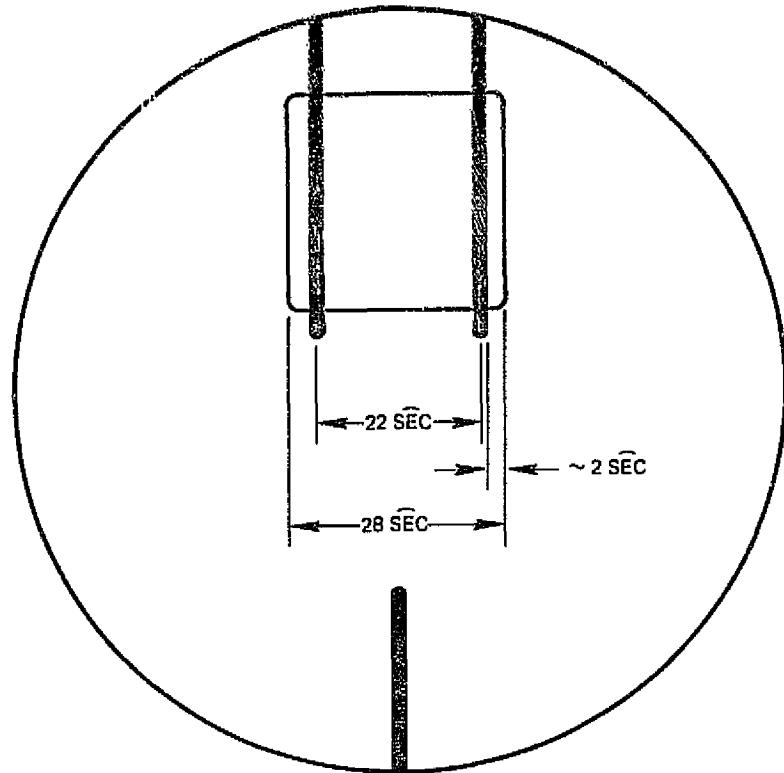


Figure 4-22. Theodolite Field of View Centering

The drawback in making such large stars is the susceptibility to non-uniformities in the illumination within the 28 arc second star. Although the stars appeared uniform visually, there is no assurance that the centroid in the spectral bandwidth of the star tracker will be at the geometrical center of the star. Based on experience gained from the unit calibrations of the strapdown star tracker (Volume II, Section 7), a 4 percent error, 1.0 arc second (1σ), was attributed to this source. Although the error could be measured by noting the star tracker output before and after rotating the star 180 degrees, this was not done because of the irrelevance of the error to the PADS test results.

Again, because of the objective of the PADS tests, it was technically justifiable to use LED sources instead of light with a spectrum more nearly approaching that of starlight. The intensity of the LED was adjusted to give the same anode current from the image dissector in the star tracker that the convolution of starlight (G_0 , 6000°K) with the nominal S20 photocathode response would produce. For the strapdown tracker, $8 M_V$ stars were

simulated; the gimbal tracker used $3.5 M_V$ stars. The tracker performance, and hence the PADS performance, is a function of the anode current, and is insensitive to the spectrum of the light producing the current, providing the intensity is such as to always produce the same current.

The collimation accuracy of the reflective bench is specified to be 2 arc seconds over the entire 40.6 cm aperture. Using the center star (on the focal axis), the collimation was checked around the area of the tracker and theodolite apertures shown in Figure 4-23. The theodolite together with a separate reference mirror mounted on the granite table was used. No collimation error, significant relative to the repeatability of the DKM3, was observed.

In the case of the strapdown test, a collimation error is caused by the top and bottom stars not being on the focal axis of the parabolic mirror. However, this did not cause a test error since the relative star positions were measured with the theodolite in the same position occupied by the star tracker.

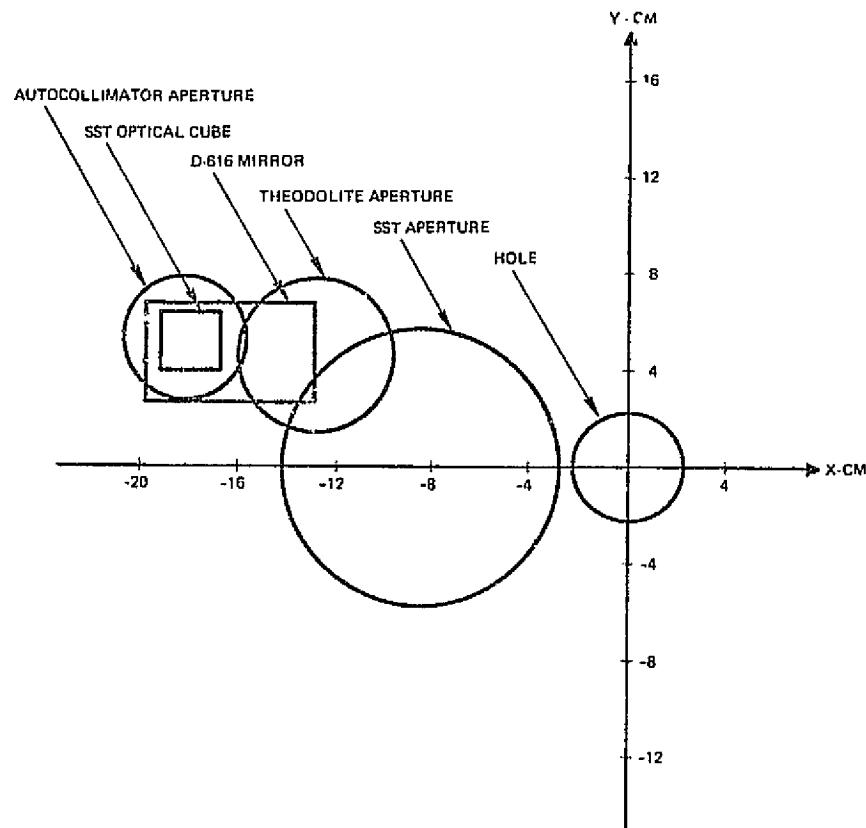


Figure 4-23. Aperture and Mirror Geometry

4.4.2.2 Double-Sided Mirror

The double-sided mirror is a Davidson (Model D-616) adjustable reference mirror. By manufacturer specification the two first-surface mirrors are parallel to within one arc second.

Non-parallelism between the two mirror surfaces will result in a one-to-one non-parallelism between the center star beam and the automatic autocollimator beam. This will appear as an absolute error common to all stars. Since this type of error is not relevant to determining the performance of the PADS systems, the parallelism was not checked in the laboratory.

4.4.2.3 Theodolite

The theodolite serves two functions:

- 1) Alignment of the center star and automatic autocollimator beams to a parallel condition
- 2) Measurement of the relative angles between the three stars used in both the strapdown and gimbal system tests.

These functions are the limiting factors in the accuracy of the laboratory instrumentation for the PADS tests. Consequently, the Kern Model DKM3 theodolite was used throughout the testing since it provides significantly better readout precision than other theodolites.⁽⁵⁾

Alignment of the star and autocollimator beams involves two steps:

- 1) Centering of the star in the telescope crosshairs
- 2) Adjustment of the double-sided mirror to center the autocollimating reticule return image in the crosshairs.

Although the micrometer readout was used to facilitate the first step, final verification of the alignment was through the telescope eyepiece and was independent of readout repeatability errors.

Repeatability in centering either the square star image or the reticule image in the crosshairs was measured indirectly by making two sets of measurements:

- 1) Sixteen micrometer readings wherein only the micrometer was moved after each reading
- 2) Sixteen micrometer reading wherein both the micrometer and the telescope were moved.

No statistically significant difference in the standard deviations of the two sets of readings was observed. The conclusion reached was that the centering repeatability is better than the readout repeatability. The latter falls within the range 0.2 to 0.4 arc second (1σ), depending on the ability and disposition of the observer. Arbitrarily, the centering repeatability was assigned the value 0.2 arc second (1σ).

A bias error in the alignment of the two beams can be introduced by the autocollimation technique used in the DKM3. A cube beamsplitter is used and the crosshair pattern and the autocollimating negative reticle are fixed to the sides of the cube. Coincidence of the telescope and autocollimating boresights was measured by first aligning the star and double-sided mirror, and then plunging and reversing the theodolite and measuring any indicated deviation. The misalignment between boresights was found to be 0.7 arc seconds for the horizontal axis and negligible relative to the readout repeatability for the vertical axis.

A final error source which must be considered in the alignment of the two beams is the spherical aberration of the DKM3. This error arises because half the aperture of the telescope is covered by the double-sided mirror. It was minimized by adjusting the telescope focus so that no discernable star motion was observed with either a full aperture or half-covered aperture. Once set, the focus was not moved throughout the ten day system test.

Measurement of the angular position of the top and bottom stars relative to the center star is subject to three types of errors:

- 1) Micrometer readout repeatability
- 2) Horizontal and vertical circle accuracy
- 3) Horizontal axis runout (gimbal test only).

The first error can be minimized by repeated readings. No instrumentation was available to measure the second error. However, circle accuracy for the DKM3 instrument has previously been measured⁽⁶⁾ as 0.2 to 0.3 arc second (1σ). Arbitrarily, 0.2 arc seconds (1σ) was assumed. Since the three stars for the gimbal system test are approximately 20 degrees apart, bearing runout in the horizontal axis of the theodolite is a factor. Unfortunately, no information is available for this error source.

Leveling of the theodolite can easily be accomplished within one or two arc second. In the case of the three stars for the strapdown system test, where the maximum star separation is 911 arc seconds, this is a negligible error source. For the three stars in the gimbal system test this error source is irrevant since only the relative star positions are measured with the theodolite. Their absolute alignment relative to the gimbal star tracker axes is determined using the star sensor boresight as explained in Section 10.2.

4.4.2.4 Air Bearing Table Readout

The air bearing table and readout electronics are made by Fecker Systems Division, Owens-Illinois. The performance parameter critical to the PADS system tests is the stability of the angle readout. This readout is a 21 bit digital word with a scaling of $360^{\circ}/2^{21}$ counts, or approximately 0.6 arc second/count.

Following a four hour warmup period, the stability of the readout was checked by positioning the table so that an equal motion in either direction was required to change the readout by one bit. No change in the readout was noted thereafter for periods up to 24 hours.

For the strapdown system test the table readout is used over a $1/2^{\circ}$ interval to provide a laboratory measurement of the horizontal location of a star in the tracker 1° by 1° field of view. Consequently, the readout was calibrated over this range using two different makes of theodolites to provide independent references. A Kern DKM3 and a Wild T3 were the theodolites used in the calibration.

Five calibrations were made using the T3 over a period of 12 days. Two months later three calibrations were made with the DKM3. A different section of a theodolite circle was used for each calibration with that instrument.

The results of the T3 and DKM3 calibrations are shown in Figure 4-24. The agreement between theodolites is excellent. The temporal stability of the error is also high since the curves were taken two months apart.

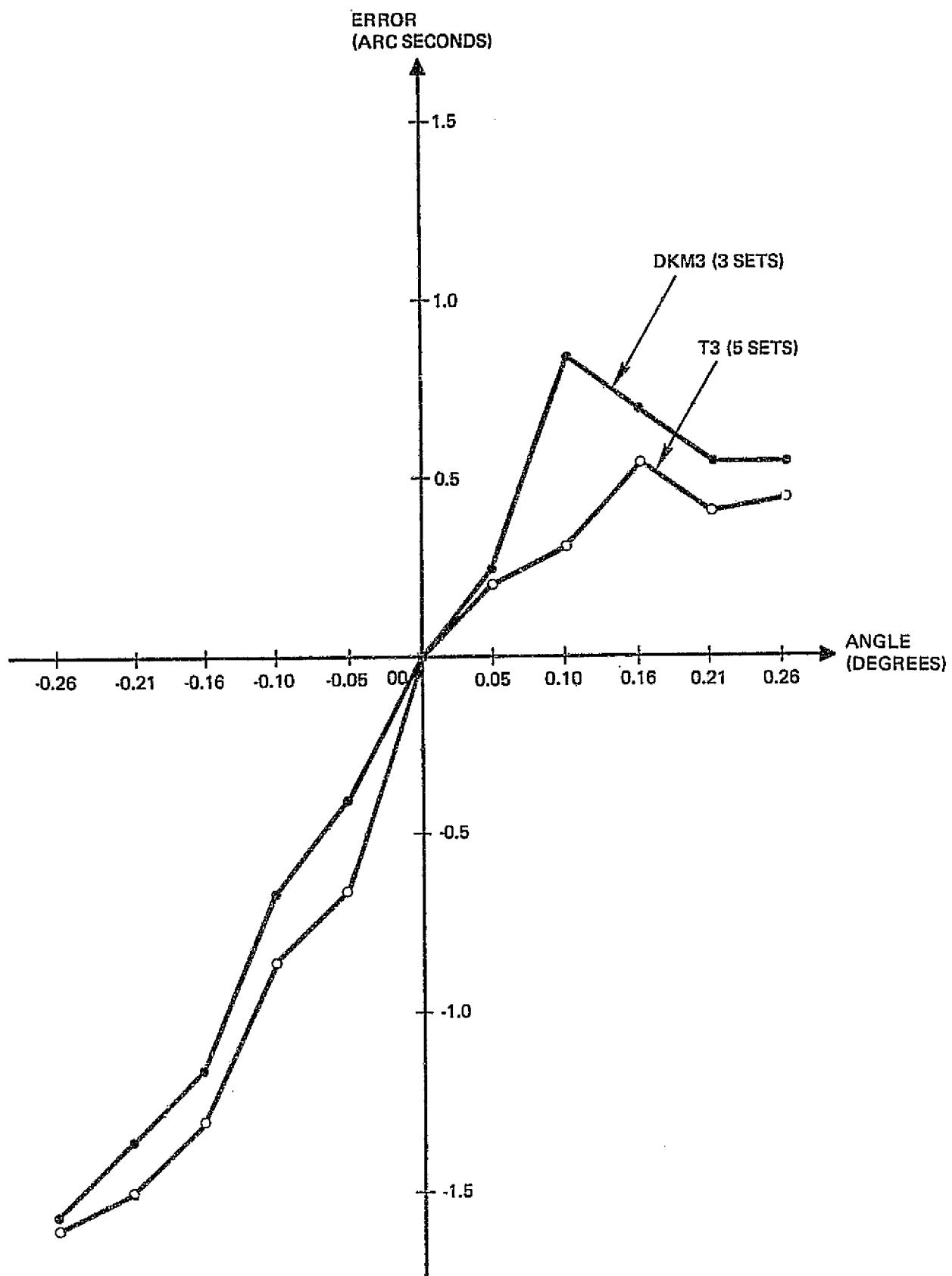


Figure 4-24. Data Results over $1/2^{\circ}$ Interval

A 256 cycle error is expected in the readout since a 512 pole Inducto-syn is used. Consequently, the data in Figure 4-24 was modeled as

$$y_1 = x_1 + \left[\sin 2\pi \left(i - \frac{N+1}{2} \right) \frac{\Delta\theta}{\theta_p} \right] x_2 + \\ + \left[\cos 2\pi \left(i - \frac{N+1}{2} \right) \frac{\Delta\theta}{\theta_p} \right] x_3, \quad i = 1, 2, \dots, 11$$

where

$$N = 11$$

$$\Delta\theta = 188 \text{ arc seconds}$$

$$\theta_p = 5062.5 \text{ arc seconds}$$

The observation equation for all data points representing the average of the two curves in Figure 4-24 is

$$y = Ax$$

The best fit in the least squares sense is

$$\hat{x} = (A^T A)^{-1} A^T y$$

Solution of this equation using a computer program gave the parameters

$$x_1 = -0.8$$

$$x_2 = 1.2$$

$$x_3 = 0.8$$

The standard deviation of the residues between the model and the 11 data points was 0.1 arc second.

In the case of the strapdown system test a total of three measurements in the field of view were made per star transit. Consequently, the optical angle (twice the table angle) quantization is

$$Q_S = \frac{3}{\sqrt{3}} \frac{2(0.6)}{\sqrt{12}}$$

$$Q_S = 0.6 \text{ arc second } (3\sigma)$$

For the gimbal system test a single measurement is taken per transit. In addition, the optical and table angles are the same. The quantization is then

$$Q_G = 3 \frac{0.6}{\sqrt{12}}$$

$$Q_G = 0.5 \text{ arc second } (3\sigma)$$

The response of the table readout to a constant rate is 1 arc sec per rad/sec. Since the maximum table rate during testing was 15 arc seconds/second, the lag in the angle readout is negligible.

4.4.2.5 Automatic Autocollimator

The two-axis autocollimator used in the PADS tests was a Davidson (Model 696) Automatic Autocollimator. The excitation of the output potentiometer was adjusted to give a scaling of 0.15 v/arc second.

For all of the test runs the output of either axis of the autocollimator never exceeded ten arc seconds. Since the excitation voltage was controlled to better than 1 percent, the scale factor error never exceeded 0.1 arc second. Of greater importance was a nonlinearity in the potentiometer output for the horizontal axis near null. This error amounted to 0.3 arc seconds deviation from an otherwise linear output.

The noise in the autocollimator output was filtered through a 20 second RC time constant mechanized in the digital computer. This reduced the noise level to 0.2 arc second (peak).

With the parallel beam star stimulus technique the bias drift of the autocollimator is calibrated before each star transit. This is accomplished by first directing the star and autocollimator beams at the theodolite and double-sided mirror and measuring the autocollimator bias. Next the beams are directed at the star tracker. A change in output between positions indicates the angle between the star beam and the normal to the reference mirror surface on the tracker.

The maximum drift of the autocollimator output observed during any of the eight test runs was 2 arc seconds for a four hour period. Since it took approximately 5 minutes of data to measure the steady-state output values at the reference and star positions, the effect of the drift was negligible.

5. TEST FACILITY DESCRIPTION

A general description of the PADS precision test facility is presented in this section. The facility layout, test equipment, and electronics are discussed.

5.1 FACILITY LAYOUT

The PADS precision test facility is located in TRW Building M5, Room 0222, Manhattan Beach, California. The test facility consists of four areas: 1) a laboratory, 2) a control platform, 3) a computer area, and 4) a work area. Figure 5-1 is a floor plan of the facility.

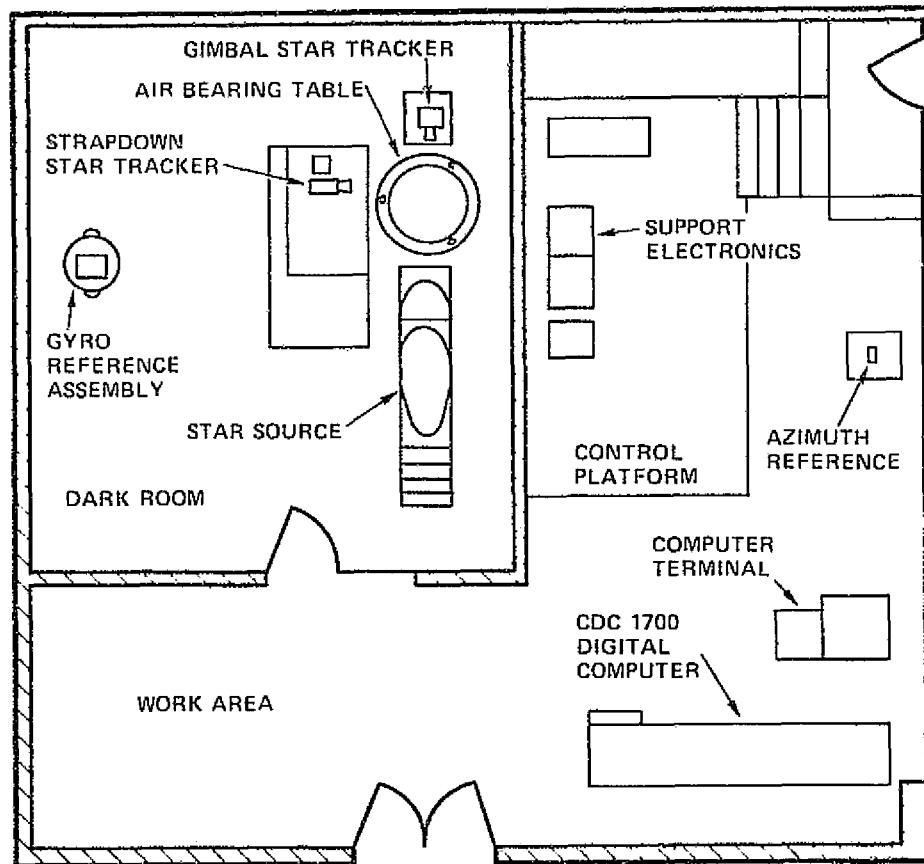


Figure 5-1. Test Facility Floor Plan

The laboratory is a dark room which is located on a seismic pad isolated from building vibrations. The pad rests on a sand base. The laboratory has its own air conditioning system which controls the air

temperature to 0.6°C. Whenever it was practical, all heat generating test equipment was located on the control platform to minimize thermal gradients within the laboratory. Equipment installation settling times greater than 60 days were allowed for both rotary tables, the granite tables, and the star source.

All electronic equipment necessary to monitor and control the system tests was located on the control platform. This area functioned as the center of activity throughout a test run.

The computer area contained the CDC 1700 digital computer and two computer control terminals. Although this computer implemented the control of various equipment during a test run, control of the computer itself was exercised from switches on the control platform. The terminals were used to initialize the program before a test run and for debugging.

A photographic montage of the facility is shown in Figure 1-3. The top photograph (a split photo) shows the inertial reference unit on the left together with its console and the rate table console. Since a ground-fixed test method was used, the rate table console was inoperative during all test runs. The star trackers and their associated test equipment are shown on the right. The test console shown on the rear wall is for unit testing of the strapdown star tracker and was also inoperative during the test runs. In addition to the two electronic consoles on the control platform, two stripchart recorders were present to display quick look data, an oscilloscope for troubleshooting electronic failures, and a desk and bookcase for data storage.

5.2 LABORATORY TEST EQUIPMENT

The test equipment used in the laboratory for both the strapdown and gimbal system tests is listed in Table 5-1. The item numbers refer to the balloon numbers in Figures 4-2 and 4-3 which are isometric drawings of the laboratory configurations. Items 28 through 31 are not shown in the figures. Item 28 is a shutter to block the autocollimator light beam from entering the star tracker aperture. Items 29 through 31 were used for initial alignment of the laboratory equipment. Item 32 monitored the laboratory temperature.

Table 5-1. Laboratory Equipment

Item	Test		Name	Type	Relevant Specification
	Strap	Gim			
1	X	X	Star Source	Davidson Reflective Bench Model D-278	2 arc sec collimation accuracy
2	X	X	LED Point Sources	TRW	
3	X	X	Table	TRW	
4	X	X	Autocollimator Stand	TRW	
5	X	X	Automatic Autocollimator	Davidson Model D-696	0.1 arc sec resolution
6	X	X	Adjustable Mirror	Davidson Model D-616	1/8 wavelength flatness
7	X		Rotating Mirror	Ransom 10 in. diameter	1/10 wavelength flatness
8	X		Mirror Mount	TRW	
9	X	X	Air Bearing Table	Fecker Dwg 256-001	0.6 arc sec readout resolution
10	X	X	Theodolite	Kern Model DKM3	0.2 arc sec accuracy
11	X	X	Adjustable Mirror	Davidson Model D-616	1/8 wavelength flatness
12	X		Mirror Stand, Strapdown Test	TRW	
13	X	X	Granite Table	Collins Microflat	
14	X	X	Granite Slab	Collins Microflat	
15	X		Strapdown Star Tracker	TRW	
16	X		Optical Cube	Mark Optical	1/8 wavelength flatness
17	X		Star Tracker Stand	TRW	
18	X	X	Rate Table	Inland Model 712	
19	X	X	Inertial Reference Assembly	NASA/GSFC OAO	
20	X		Deflection Mirrors	Ransom 10 in. diameter	1/10 wavelength flatness
21	X		Rotating Mirror Fixture	TRW	
22	X		Stationary Mirror Fixture	TRW	
23	X		Reference Mirrors	Rolyn	1/8 wavelength flatness
24	X		Gimbal Star Tracker	TRW	
25	X		Granite Riser	Collins Microflat	
26	X		Granite Block	Collins Microflat	
27	X	X	Mirror Stand, Gimbal Test	TRW	
28	X	X	Shutter Assembly	TRW	
29	X	X	Theodolite	Wild T3	0.2 arc sec accuracy
30	X	X	Vertical Mirror	Farrand No. 88504	2 arc sec to vertical
31			Bubble Level	Starrett No. 199	1 arc sec resolution
32	X	X	Temperature and Humidity Gauge	Honeywell	

5.3 ELECTRONIC EQUIPMENT

The general approach to the design of the electronics was to provide redundancy and to avoid interdependence of equipment. The intent of both of these ground rules was to avoid delays during the equipment integration phase. Redundancy was provided for both the strapdown star tracker and the gyro readouts by having their unit test consoles on hand. This allowed their integration in the laboratory without dependence on the facility electronics. The facility electronics had the capability to duplicate the computer commands, thereby allowing operation of the laboratory equipment while the computer programs were being debugged. Operation of the equipment without either of the star trackers, or the gyros, was provided in order to avoid delays in the case of a malfunction of any of the units. Since it was a critical element, a backup automatic autocollimator was on hand. A complete supply of electronic components was maintained in the facility.

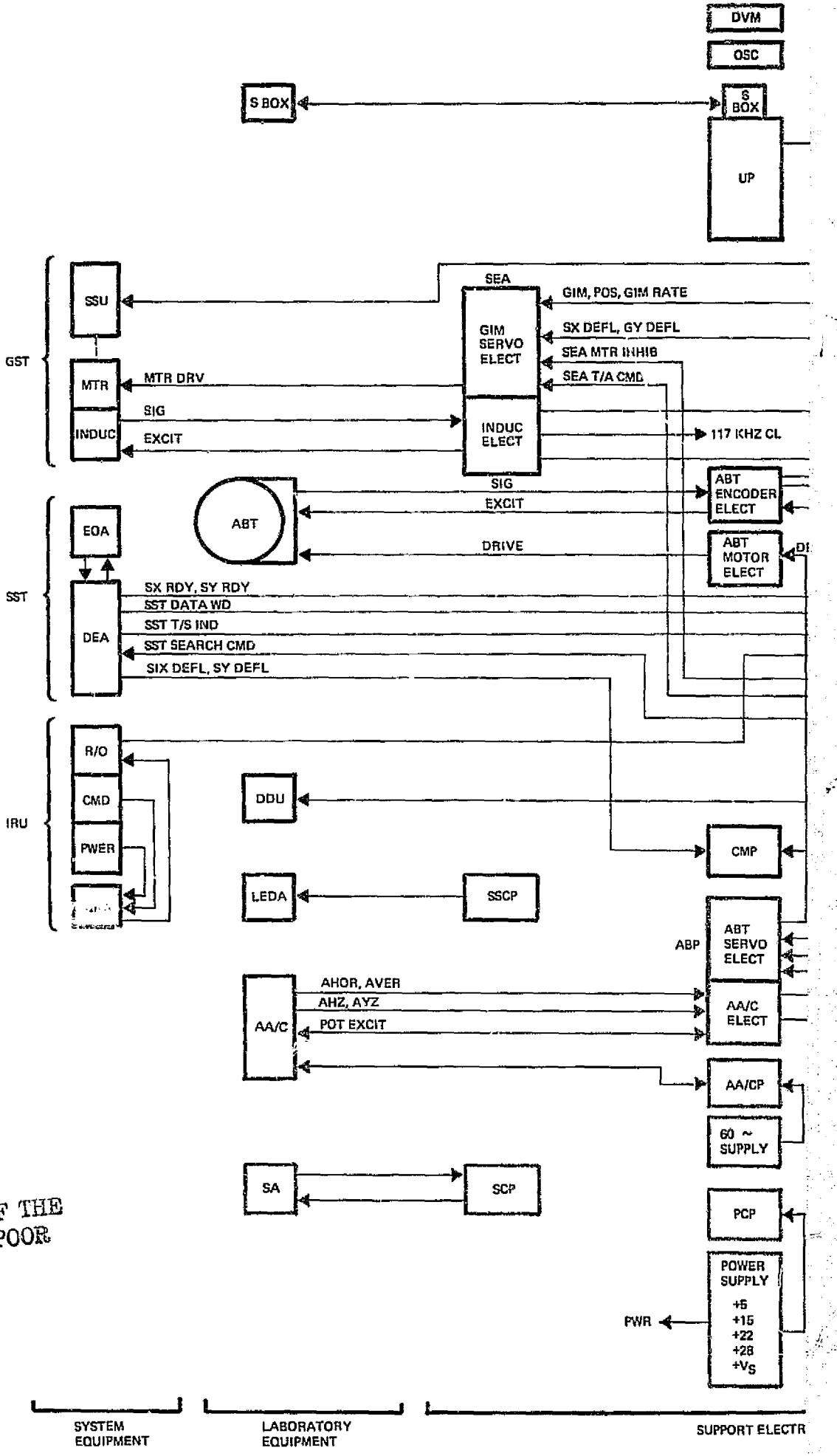
A block diagram of the electronic equipment in the PADS test facility is shown in Figure 5-2. An explanation of the acronyms used is given in Table 5-2. Figures 5-3 through 5-9 are photographs of the electronics located on the control platform. Functional descriptions of the panels in the two consoles are given in the following paragraphs.

AA/CP. This panel, supplied by Davidson Optronics, controls the automatic autocollimator unit in the laboratory. After initially setting the track loop gains, the panel was used only to indicate acquisition of an optical flat by the autocollimator.

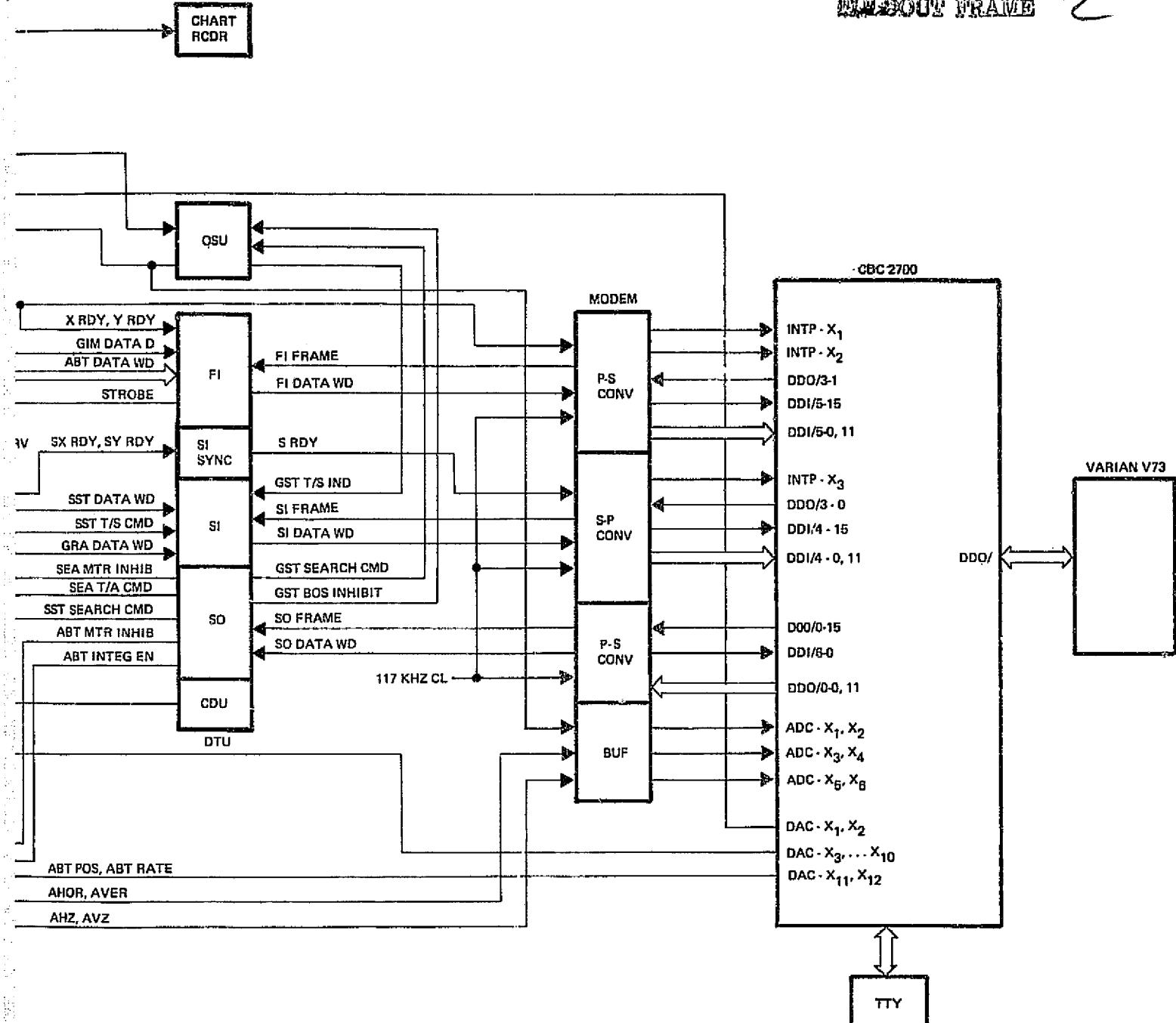
ABP. This panel performs two functions: 1) it provides the servo electronics to drive the ABT, and 2) it supplies the excitation and buffer amplifiers for the AA/C potentiometers.

The computer supplies two analog voltage commands, position and rate, to the servo electronics. The electronics implements a proportional plus integral drive to the ABT power amplifiers. A potentiometer is available on the panel to sum a voltage in with the computer position command. This capability allows manual positioning of the table.

NOT INPUT FRAME



COMPOSITE FRAME



ONICS

COMPUTER I/O
ELECTRONICS

DIGITAL COMPUTERS

Table 5-2. Electronic Interface Acronyms

AA/C	Automatic Autocollimator	OSC	Oscilloscope
AA/CP	AA/C Control Panel	OSU	Optical Sensor Unit
ABP	Analog Buffer Panel	P-S	Parallel to Serial
ABT	Air Bearing Table	PCP	Power Control Panel
BUF	Buffer	PWR	Power
CDU	Control Room Display Unit	RCDR	Recorder
CMD	Command	R/O	Readout
CMP	Console Monitor Panel	RPP	Remote Patch Panel
DDU	Darkroom Display Unit	SA	Shutter Assembly
DEA	Digital Electronics Assembly	S Box	Speaker Box (Intercom)
DTU	Data Transfer Unit	SCP	Shutter Control Panel
DVM	Digital Voltmeter	S-P	Serial to Parallel
EOA	Electro-Optical Assembly	SEA	Sensor Electronics Assembly
FI	Fast Input	SI	Slow Input
GRA	Gyro Reference Assembly	SO	Slow Output
GST	Gimbal Star Tracker	SS	Star Source
INDUC	Inductosyn	SSCP	Star Source Control Panel
IRU	Inertial Reference Unit	SSU	Star Sensor Unit
LEDA	Light Emitting Diode Assembly	TTY	Teletypewriter
MTR	Motor	UP	Utility Panel

The excitation to the AA/C potentiometers is independently adjustable. A scale factor of 0.15 volt/arc second was used. The buffer amplifiers send the potentiometer outputs to the computer.

CMP. This panel monitors the gimbal motor current, the SST analog deflection signals, and eight DAC channels from the computer. The SST deflection signals were displayed on the oscilloscope. The DAC channels were displayed on the stripchart recorder via the UP.

UP. This panel provides direct connection to the two stripchart recorders. An eight channel and a six channel recorder are available. The eight channel was used for quick look information during a test run. The six channel was for long term monitoring of the gyro performance because it could be operated at a very slow chart rate.

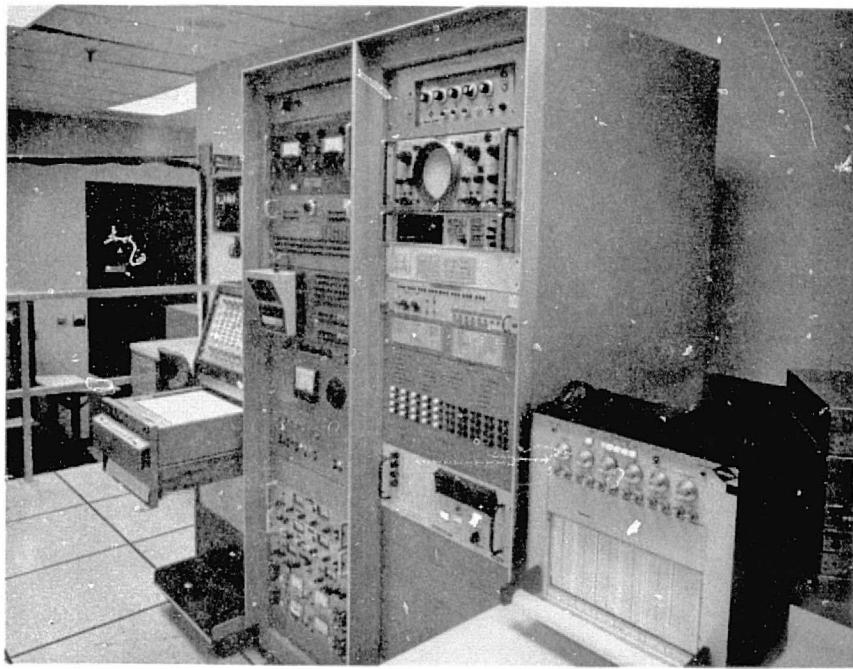


Figure 5-3. Control Platform View -- Right



Figure 5-4. Control Platform View -- Left

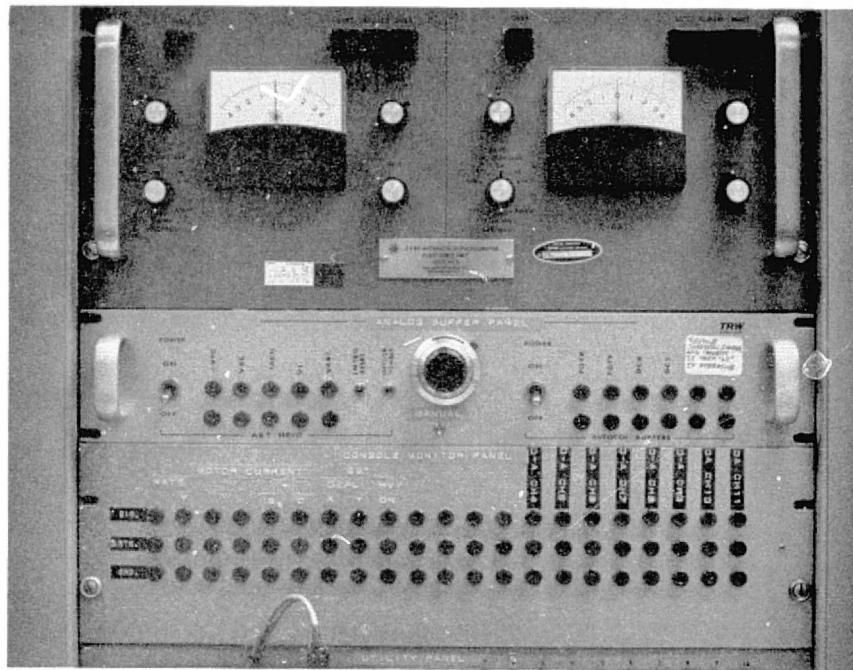


Figure 5-5. AA/CP to Up Panels

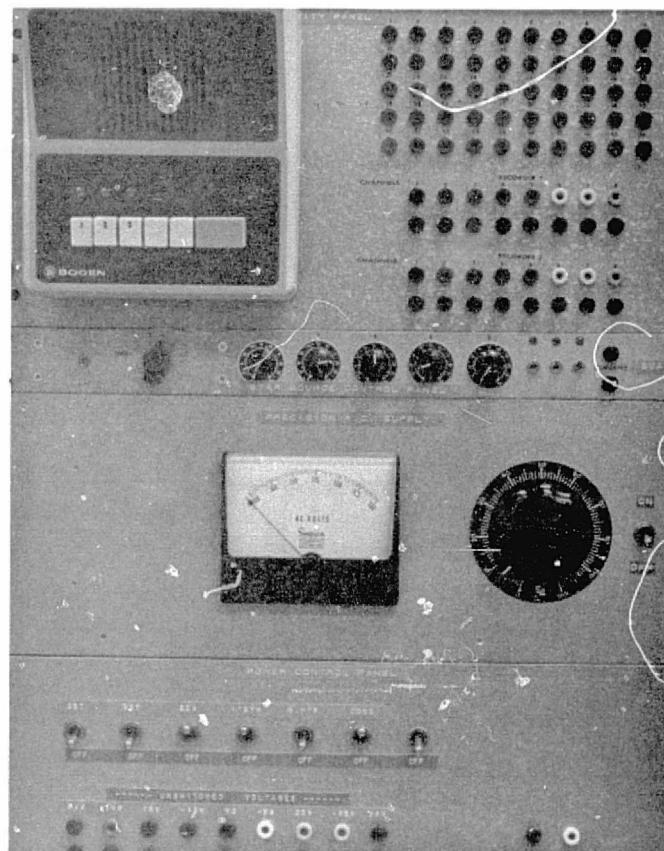


Figure 5-6. Up to PCP Panels

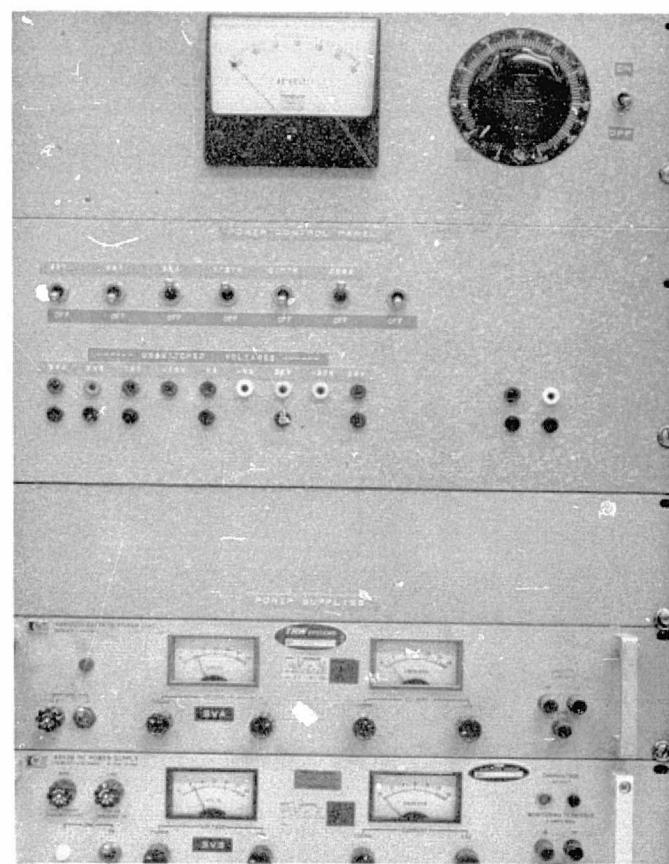


Figure 5-7. PCP Panel and Power Supplies

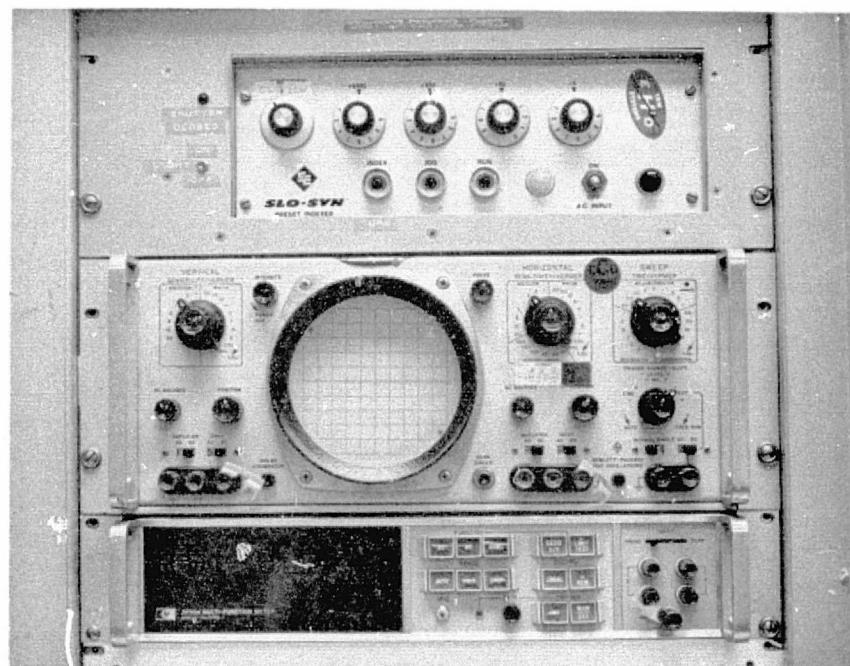


Figure 5-8. SCP to DTU Panels

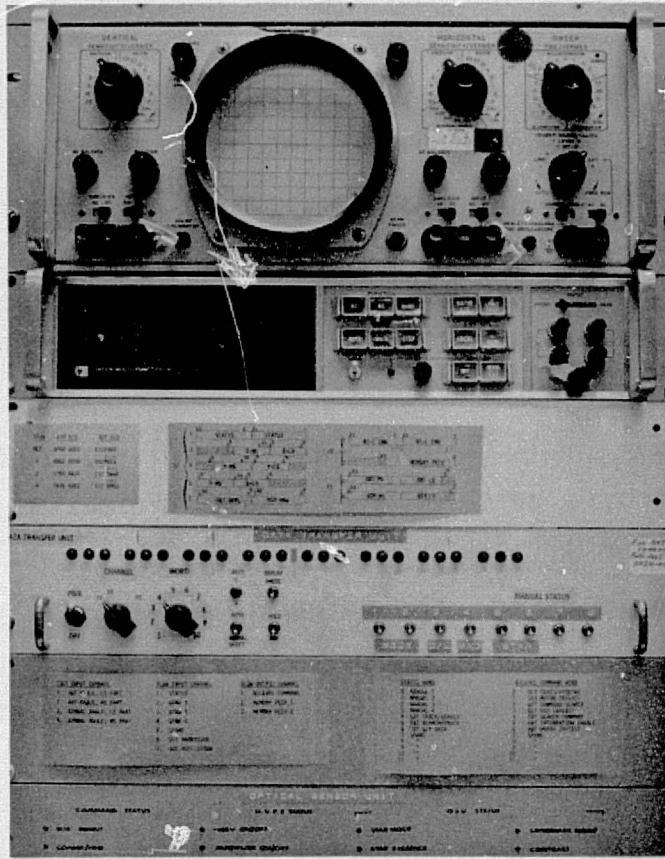


Figure 5-9. DTU and OSU Panels

PCP. This panel provides independent switching of the dc power supplies to the other panels and equipment. The purpose is to avoid power supply turn-on transients.

SCP. This panel operates the shutter in front of the AA/C. Since it was essential to avoid having the AA/C light beam enter the strapdown star tracker, a fail-safe light indicator is inserted in the panel to signal shutter closure.

DTU. This panel performs four functions: 1) it transfers all digital signals from the ABT, GST, SST, and IRU to the computer, and 2) it transfers digital signals from the computer to the ABT electronics, GST, and SST, 3) it displays digital information from the computer and from the ABT, GST, SST, and IRU, and 4) it provides commands to the computer program.

Digital data transfer into the computer is accomplished at two rates: 1) 6 msec/word (FI), and 2) 50 msec/word (SI). The ABT and GST gimbal angles are sent at the fast rate. SST deflection and magnitude, three gyro outputs, and a status word are sent at the slow rate.

Data transfer from the computer is accomplished on one channel (SO) at the rate of 50 msec/word. A command word and two memory peek words are transmitted. Individual bits of the command word are sent to the ABT electronics, the GST, and the SST. The memory peek words display program selected memory locations in the computer.

Any of the above digital words can be shown on the LED display on the panel by using the selector switches. This information can also be duplicated on a similar LED display in the laboratory.

In order to minimize operating personnel, the computer program was designed to be operated from the DTU by the test conductor. This is implemented from eight switches on the panel which set the state of eight bits in the status word sent on the SI channel.

An optional capability of the DTU is the ability to function without the computer. This allowed display of the ABT, GST, GRA, and SST signals while the computer was being used for other tasks.

OSU. This panel displays the status of the SSU. It also has a switch to enable the SSU high voltage supplies. The SSU analog deflection signals were displayed on the oscilloscope.

ABT ENCODER ELECTRONICS. This panel, supplied by Fecker, provides a visual display of the 21 bit digital word indicating the table angle. It also sends this word in parallel to the DTU.

ABT MOTOR ELECTRONICS. This panel functions as a power amplifier to drive the ABT motor.

In addition to the above described panels a MODEM panel in the CDC 1700 computer was designed. This panel functions both as a signal buffer and as a serial/parallel digital word converter.

The CDC 1700 computer has the capability of transmitting information to the Varian V73 computer. This capability was used to store the PADS test run data using the magnetic tape unit on the V73.

6. DATA HANDLING AND DISPLAY

Data was generated during the PADS system test from two sources: the PADS sensors and the laboratory instrumentation. This is illustrated in Figure 6-1. The data was collected for two purposes: 1) to provide the basis for the evaluation of the performance of the PADS system under test, and 2) to provide real time diagnostic data to indicate the validity of the test.

All data was transmitted to the CDC 1700 computer via the data transfer electronics. The data necessary for the evaluation of the PADS system was stored on magnetic tape. This data was transmitted to the V73 computer over data lines for storage on the tape since the CDC 1700 did not have a magnetic tape unit. The real time diagnostic data was displayed during a test run on an eight channel stripchart recorder via the test display electronics.

The following sections describe in detail the test performance and real time diagnostic data which was collected.

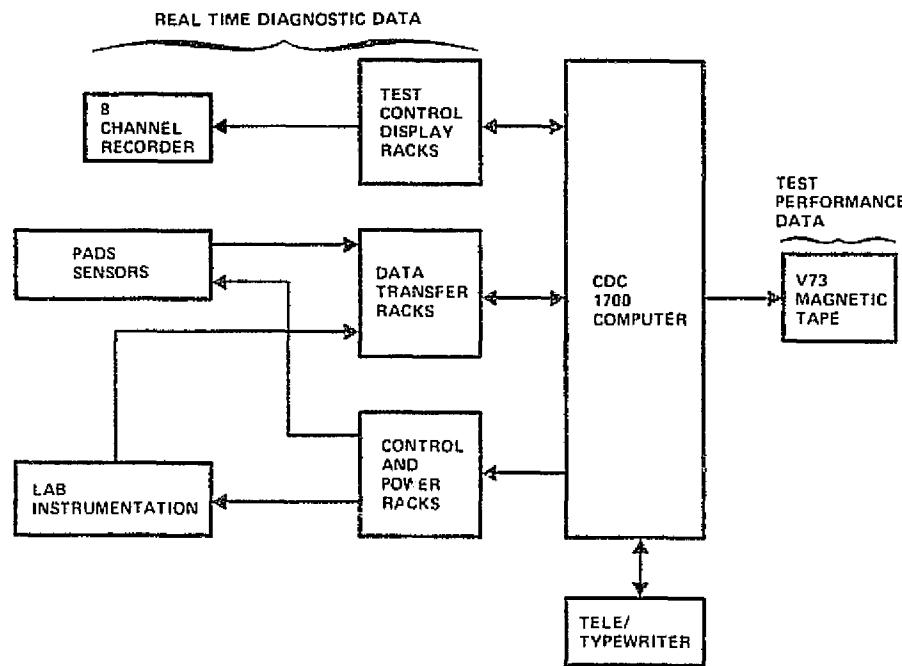


Figure 6-1. Data Handling and Display

6.1 TEST PERFORMANCE DATA

Three types of performance data were stored on magnetic tape for both the strapdown and gimbal system tests. These are listed in Table 6-1. PADS data consists of the gyro and star tracker signals. This information is used in the PADS algorithms to estimate the inertial attitude of the PADS axes. Lab data consists of the air bearing table angle and automatic autocollimator differences. This information, together with pretest measurements, identifies where the star is relative to the PADS axes, and, ultimately, the true inertial attitude of the PADS axes. Boresight data consists of filtered star tracker and automatic autocollimator signals. In essence it measures the static boresight stability of the tracker.

Table 6-1. Types of Performance

Data Word	PADS Data	Lab Data	Boresight Data
<u>Strapdown System Test</u>			
T	X	X	
GRAX	X		
GRAY	X		
GRAZ	X		
SSTX	X		
SSTY	X		
ABTA		X	
<u>A_A/CX</u>		X	
<u>A_A/CY</u>		X	X
SSTX			X
SSTY			X
<u>Gimbal System Test</u>			
T	X	X	
GRAX	X	X	
GRAY	X		
GRAZ	X		
GSTX	X		
GSTY	X		
GSTA	X		
ABTA		X	
<u>A_A/CX</u>		X	
<u>A_A/CY</u>		X	X
GSTX			X
GSTY			X
GSTA			X

The first two data types provide the basis for the evaluation of the PADS performance; namely, the difference between the estimated PADS attitude from the sensor information and the true attitude from the laboratory instrumentation data. The third data type was included for two reasons: 1) to provide a check on the validity of the lab data accuracy, and 2) to measure the boresight stability of the star trackers throughout the test period.

Data was collected every second for both system tests. The word T is the time tag. The three-axis gyro information, GRAX, GRAY, and GRAZ, was collected continuously throughout the test run. Every 20 minutes, during a star transit, the star tracker information was collected. For the strapdown tracker the horizontal and vertical positions of the star in the field of view, SSTX and SSTY, were stored. The same signals for the gimbal star tracker, GSTY and GSTX, were collected, along with the gimbal angle, GSTA. The air bearing table angle, ABTA, was also collected during a star transit. The duration of the transit was approximately four minutes for the strapdown test and two minutes for the gimbal test. As described in Section 4.3 the autocollimator bias was calibrated prior to each star transit by pointing the parallel star and autocollimator beams at the theodolite and double-sided mirror. Following this calibration the static orientation of the star relative to the PADS axes was checked by pointing the parallel beams at the star tracker and its reference mirror surface. The star orientation was indicated by the autocollimator outputs, minus the bias errors, namely, $\overline{\Delta AA/CX}$ and $\overline{\Delta AA/CY}$. With the star pointed at the tracker, the output signals from the tracker were also collected: \overline{SSTX} and \overline{SSTY} for the strapdown tracker, and \overline{GSTY} , \overline{GSTX} , and \overline{GSTA} for the gimbal tracker. The bar over these signals indicates that they are filtered to minimize their noise content. These filtered signals were stored once at the start of each star transit.

It is noted that the horizontal star position is indicated by the signals SSTX, GSTY, and $\Delta AA/CX$; the vertical by SSTY, GSTX, and $\Delta AA/CY$.

All data was converted into engineering units in the V73 computer before storage on the magnetic tape. Time was carried to a precision of 0.001 second, and all angles were carried out to 0.1 arc second. For a four hour run, with 12 star transits, the number of words stored on tape was approximately 78,000 for the strapdown system, and 69,000 for the gimbal system.

In the case of the gyro data the accumulated attitude was transmitted from the gyros and stored on tape. The advantage of this approach, compared to transmitting the incremental attitude, was that a random transmission error would not invalidate the long term knowledge of gyro attitude change.

6.2 REAL TIME DIAGNOSTIC DATA

The real time diagnostic data provided a continuous indication throughout a test run that the functional operation of the hardware was proper and that, with a high degree of probability, the test data being collected was valid in terms of indicating the PADS performance. This information was considered necessary in view of the length (4 to 5 hours) of the test runs. It eliminated any time which would have been wasted by continuing to run invalid tests.

The different types of diagnostic data that were used are listed in Table 6-2. All of the performance data signals listed in Table 6-1 were monitored by the stripchart recorder, the ABT readout, and the DTU LED display. The teletypewriter and the CRT display provided error messages indicating either a procedural error by the test conductor or a data transmission error.

Table 6-2. Types of Realtime Diagnostic Data

Stripchart Recorder

<u>Channel</u>	<u>Strapdown Test</u>	<u>Gimbal Test</u>
1	Δ GRAX	Δ GRAX
2	Δ GRAY	Δ GRAY
3	Δ GRAZ	Δ GRAZ
4	SSTX	GSTX
5	SSTY	GSTY
6	AA/CX	AA/CX
7	AA/CY	AA/CY
8	ERROR	ERROR

Air Bearing Table Readout

ABTA

DTU Led Display

GSTA

CDC 1700 Teletypewriter

Operator Error Message

V73 CRT Display

Transmission Error Message

The stripchart recordings for the four strapdown system test runs and the four gimbal system test runs are included in Appendix D. The gyro signal, ΔG_{RA} , is the attitude change over a 100 second time period. The filtered horizontal and vertical autocollimator signals are AA/CX and AA/CY, respectively. The signal ERROR is the filtered difference between the star tracker horizontal axis signal and the air bearing table angle, biased to zero at the center of the tracker field of view. This signal occurred only during a star transit. The square wave discernible in the autocollimator signals reflects the two positions, one with the parallel beams pointed at the theodolite, the other with the beams pointed at the star tracker. The majority of the time between star transits was spent at the latter position. A peculiarity in the gyro data is that occasionally the digital to analog converter in the CDC 1700 will turn over if the signal is near ± 10 volts. The result is a discrete change of 10 volts in the recorder output. This can be observed, for example, in the GRAZ signal in the first strapdown system test on 1 October 1975.

The air bearing table angle was observed during the test directly from the Fecker readout display. The gimbal angle was observed on the DTU LED display.

If the test operator followed an incorrect sequence in switching between program modes, the computer program printed an error message at the teletypewriter.

To provide a final data check before storage of the data on magnetic tape, the V73 computer program performed a check on the time word, T, to verify that one second occurred between successive words.

7. LABORATORY COMPUTER PROGRAMS

Two categories of computer programs were written for the CDC 1700 computer in the PADS test facility. The first provided for a step-by-step integration and checkout of the laboratory and system equipment. The second category consisted of the system test programs for the strapdown and gimbal system tests. These two programs are described in detail in this section since they are essential to a complete understanding of the tests.

The purpose of either system test program was twofold: 1) to provide star stimuli to the star tracker; and 2) to collect, store, and display the signals from the PADS sensors and the laboratory instrumentation. The star stimuli consisted of individual star transits in which a collimated star beam was moved past the field of view of the star tracker at earth rate. The frequency of the star transits as well as the length of the test were determined by the test conductor. All data was time-tagged and stored on magnetic tape. Separate programs were written for the strapdown and gimbal system tests due to the differences in operation of the star trackers. The programs were named SUE and GWEN, for the strapdown and gimbal tests, respectively.

Flow diagrams of the two programs appear in Appendix E.

7.1 STRAPDOWN SYSTEM TEST PROGRAM

The following sections describe the modes, data displays, and data collection capabilities of the strapdown system test program SUE.

7.1.1 Program Modes

There were three main program modes in SUE:

MODE 1 - REFERENCE POSITION. The star source (SS) and automatic auto-collimator (AA/C) beams were pointed at the theodolite and reference mirror by the 1700 computer closing a servo loop about the ABT R/O to drive the ABT to a reference position, ABTO = 7710000. The difference between the readout, ABTA, and ABTO was output as a position signal, POS, to the servo electronics by a 1700 DAC channel every 3 milliseconds.

Expressed in equation form,

$$POS = ABTO-ABTA, |POS| \leq 2047 \text{ bits}$$

$$POS = 2047 \text{ sign } (POS), |POS| > 2047 \text{ bits}$$

where

$$1 \text{ bit} = 0.617981 \text{ arc sec}$$

Although a rate command channel was available, it was set to zero.

MODE 2 – ZERO POSITION. The SS and AA/C beams were pointed at the strapdown star tracker (SST) by the 1700 closing a servo loop around the ABT R/O to drive the ABT to 0010000. Position and rate were commanded as in MODE 1.

MODE 3 – STAR TRANSIT. The purpose of this mode was to drive the ABT at half earth rate to sweep a simulated star across the field of view of the star tracker. Before starting this sweep, the ABT was driven from the ZERO position of MODE 2 to the starting position which places the star outside the field of view. The complete ramp function generated in the 1700, using its clock as a time reference, is defined graphically in Figure 7-1. The ramp is continued until the mode is manually exited by the test conductor. The servo position command, computed and output every 3 milliseconds was:

$$POS = (RAMP + ZEROP)-ABTA$$

where

ZEROP is the ZERO position of MODE 2

and RAMP is the function in Figure 7-1.

There were two submodes in SUE:

RUNNING AVERAGES. This submode, when exercised, computed running averages of both AA/C outputs and, if the star tracker was in track, both SST digital outputs. This submode could only be entered from MODE 1 or MODE 2. When exited the last values of the running averages were stored in memory, one pair for each mode in the case of the AA/C. Since SST outputs were available only in MODE 2, only one pair was stored.

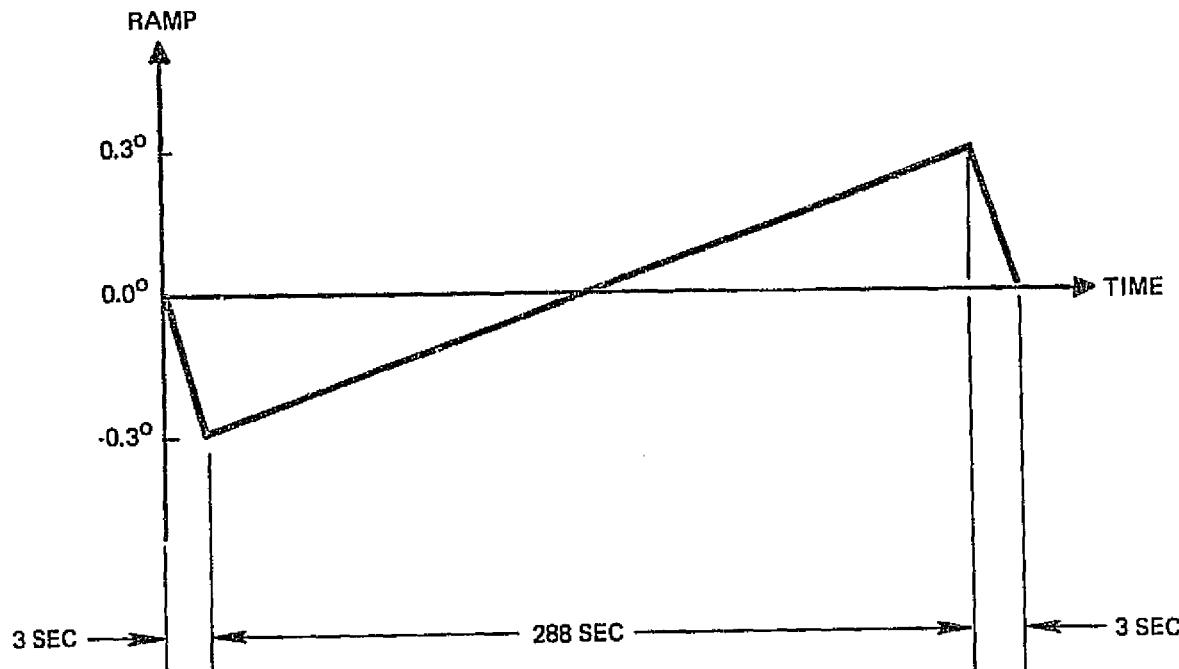


Figure 7-1. RAMP Function for the Strapdown test

DATA COLLECTION. This submode sent data to the V73 computer to be stored on magnetic tape. It could be entered or exited from any of the three main modes. Its normal duration was four hours and constituted a "test run." Since a time base was required for the test run, the 1700 clock was initialized and started when the submode was entered and stopped when it was exited. Therefore the exercise of the clock dependent functions, the ramp and the one second period for some of the running averages, required this submode to be active.

7.1.2 Mode Control

The teletypewriter was used only to start and stop the program. All other control was from four manual switches on the DTU. The switch logic for mode control is shown in Table 7-1. Switch No. 3 controlled the RUNNING AVERAGES submode. Switch No. 4 controlled the DATA COLLECTION submode. The switch positions were transmitted to the 1700 computer via the lower order four bits of the slow input status word. A one corresponded to the "UP" switch position.

Table 7-1. SUE Mode Control

Mode	Description	Switch Number			
		No. 1* Bit 0	No. 2* Bit 1	No. 3* Bit 2	No. 4* Bit 3
1	Reference Position	0	0	--	--
2	Zero Position	0	1	--	--
3	Star Transit	1	1	--	--

*Slow input status word

7.1.3 Program Discrete Commands

The program set the discrete commands from the digital output channel to the states indicated in Table 7-2.

7.1.4 Real Time Diagnostic Data

Table 7-3 lists the parameters that were sent to the stripchart recorder through the DAC channels of the 1700 computer, for display during the test.

Table 7-2. Discrete Command States

Slow Output Bilevel Command Word Bit Number	Description	State
4	SST Search	0
5	ABT Integ Enable	0
6	ABT MTR Inhibit	0
All Others	Spares	0

Table 7-3. DAC Output Data

DAC	Data	Type	Update Period	Scaling
4	<u>ΔGRA</u> X	Incremental Count	100 sec	0.1 V/count
5	<u>ΔGRA</u> Y	Incremental Count	100 sec	0.1 V/count
6	<u>ΔGRA</u> Z	Incremental Count	100 sec	0.1 V/count
7	<u>SST</u> X	Running Average	50 msec	0.5 V/count
8	<u>SST</u> Y	Running Average	50 msec	0.5 V/count
9	<u>AA/CX</u>	Running Average	1 sec	0.25 V/arc sec
10	<u>AA/CY</u>	Running Average	1 sec	0.25 V/arc sec
11	<u>ERROR</u>	Running Average	50 msec	0.5 V/count

An explanation of each data type is given below:

ΔGRA. These are the differences in the 16 bit gyro word at a 100 second interval. The scaling (1 meru = $0.015^0/\text{hr}$) is:

$$0.05 \text{ meru} = 1 \text{ count}/100 \text{ sec}$$

Since the maximum difference (at full earth rate) would be 20000 counts, less than half the capacity of a 16 bit word, differences could be taken without accounting for turnover of the gyro word. On the other hand, the DAC word, scaled for 0.1 V/count and limited to ± 10 V, could turn over.

SST. These are the running averages of the 12-bit star tracker outputs. They are computed every 50 millisec by the equation:

$$\overline{\text{SST}}_{N+1} = (1 - e) \overline{\text{SST}}_N + e (\text{SST}_{N+1})$$

where

$$e = 0.001$$

These averages were computed only in MODE 2, and were stored upon exit of the RUNNING AVERAGE submode.

AA/C. These are the running averages of the autocollimator outputs. They were computed every one second by the equation:

$$\overline{AA/C}_{N+1} = (1 - e) \overline{AA/C}_N + e (AA/C_{N+1})$$

where

$$e = 0.05$$

These averages were computed in MODE 1 and MODE 2, and were stored separately upon exit of the RUNNING AVERAGES submode.

ERROR. This is the running average of the difference between the SST horizontal axis output and the ABT readout. It is computed every 50 millisec by the equations:

$$ERROR = SSTX - 1.236 (\text{ABTA})$$

$$\overline{ERROR}_{N+1} = (1 - e) \overline{ERROR}_N + e (SST_{N+1})$$

where

$$e = 0.04$$

This average was computed only in MODE 3 when the star tracker was in track.

7.1.5 Data Collection

Collection of data to be transmitted by the 1700 computer to the V73 is initiated by DTU switch 4 in the up position. There are three different data formats. Table 7-4 lists the data to be sent for each format.

Note that "Track" actually implies two conditions: 1) that the SST Search/Track signal indicates track, and 2) that the positive ramp in MODE 3 be present. "Start of track" is the first time the 1 sec counter changes after entry into track as defined above. "Non-track" is all the rest of the time.

Table 7-4. Data Stored on Magnetic Tape

Data	Nominal Scaling	Bits Required	Non-Track	Start of Track	Track
			1/Sec	Single	1/Sec
Time	1 msec/cnt	19	X	X	X
GRAX	0.075 sec/cnt	21	X	X	X
GRAY	0.075 sec/cnt	21	X	X	X
GRAZ	0.075 sec/cnt	21	X	X	X
SST X/Y Status	--	1		X	X
SSTX	1.0 sec/cnt	12		X	X
SSTY	1.0 sec/cnt	12		X	X
ABTA	0.618 sec/cnt	21		X	X
SSTX	1.0 sec/cnt	12		X	
SSTY	1.0 sec/cnt	12		X	
AAA/CX	0.15 sec/volt	12		X	
AAA/CY	0.15 sec/volt	12		X	

Comments regarding the data are:

- TIME AND STATUS. Time must have at least 21 bits to record 4 hours of data at 10 msec/count. Time will be zero at the start of data collection. The three status bits are:
 - 1) Search/Track (SI, Status, Bit 5)
 - 2) X/Y Data (SI, Status, Bit 6)
 - 3) Initial Track (True at start of track).
- AGRA. The gyro words were corrected for their own turnovers. At a maximum rate of 200 counts/sec, only 21 bits are actually needed.
- SST. The X and Y words were sent alternately every 50 msec to the 1700 computer. The data transmitted to the magnetic tape always included the X word corresponding to the nearest time-tag.
- ABTA. The range of the table movement in SUE required only 13 of the 21 bits available.

- SST. These 2 words were the stored values from the last time the RUNNING AVERAGES submode was entered in MODE 2.
- $\Delta AA/C$. These two words were computed as:

$$\overline{\Delta AA/C} = \overline{AA/C}_{\text{mode } 3} - \overline{AA/C}_{\text{mode } 2}$$

where

$\overline{AA/C}_{\text{mode } 3}$ = stored values from the last time the RUNNING AVERAGES submode was entered in MODE 2

$\overline{AA/C}_{\text{mode } 2}$ = stored values from the last time the RUNNING AVERAGES submode was entered in MODE 1.

7.2 GIMBAL SYSTEM TEST PROGRAM

The following sections describe the modes, data displays, and data collection capabilities of the gimbal system test program GWEN.

7.2.1 Program Modes

There were three main program modes in GWEN.

MODE 1 – REFERENCE POSITION. This mode positioned the ABT such that the SS and AA/C are pointed at the theodolite and reference mirror, respectively, and pointed the GST to a nominal angle. The mode was used:

- 1) To align the SS and reference mirror before the test
- 2) To define the AA/C boresight during the test
- 3) To measure any misalignment between the SS and the reference mirror after the test.

Servo loops were closed around the ABT and GST using their readouts. Constant angles, ABTO and GSTO, were commanded. The difference between the readouts and the command angles were output unscaled as position signals to the servo electronics. To hasten acquisition, rate signals were commanded whenever the corresponding position signal saturated.

Expressed in equation form,

$$TPOS = ABTO - ABTA, |TPOS| \leq 2047 \text{ bits}$$

$$TPOS = 2047 \text{ sign (TPOS)}, |TPOS| > 2047 \text{ bits}$$

$GPOS = GST0 - GSTA$, $|GPOS| \leq 2047$ bits

$GPOS = 2047 \text{ sign } (GPOS)$, $|GPOS| > 2047$ bits

and

$TRATE = 0$, $|TPOS| < 2047$ bits

$TRATE = 2047 \text{ sign } (TPOS)$, $|TPOS| \geq 2047$ bits

$GRATE = 0$, $|GPOS| < 2047$ bits

$GRATE = -\text{sign } (GPOS)$, $|GPOS| \geq 2047$ bits (equivalent to 1^0 sec)

These equations were updated every 3 msec.

MODE 2 – ZERO POSITION. This mode positioned the ABT such that the SS and AA/C are pointed at the GST via one of the three rotating mirrors on the ABT, and moved the GST gimbal to search for and lock on to the star. The mode was used immediately prior to each star transit to measure:

- 1) Small rotations of the GST with respect to the AA/C boresight which may occur during the test
- 2) Drifts in the GST static pointing angle during the test.

The same servo loops were closed about the ABT and, during search, about the GST as in MODE 1. When the star was acquired (track), upon command of the computer, the hardware switched to a second servo loop which drove the gimbal to null the OSU vertical deflection signal.

For the computer-closed loops, the same equations as in MODE 1 applied except that ABTO and GSTO were a function of the 3 star positions which were selected manually from two switches on the DTU. The servos were updated every 3 msec.

MODE 3 – STAR TRANSIT. This mode drove the ABT in a ramp at earth rate to sweep a simulated star across the field of view strip of the GST. The ramp described in Figure 7-2 was commanded to the ABT servo loop which was identical to the loops in MODES 1 and 2. The GST gimbal was driven in the same way as in MODE 2 to search and track the star. Exit from MODE 3 terminated the ABT ramp and also the GST search if a star had not been acquired. As in MODES 1 and 2 both servos were updated every 3 msec.

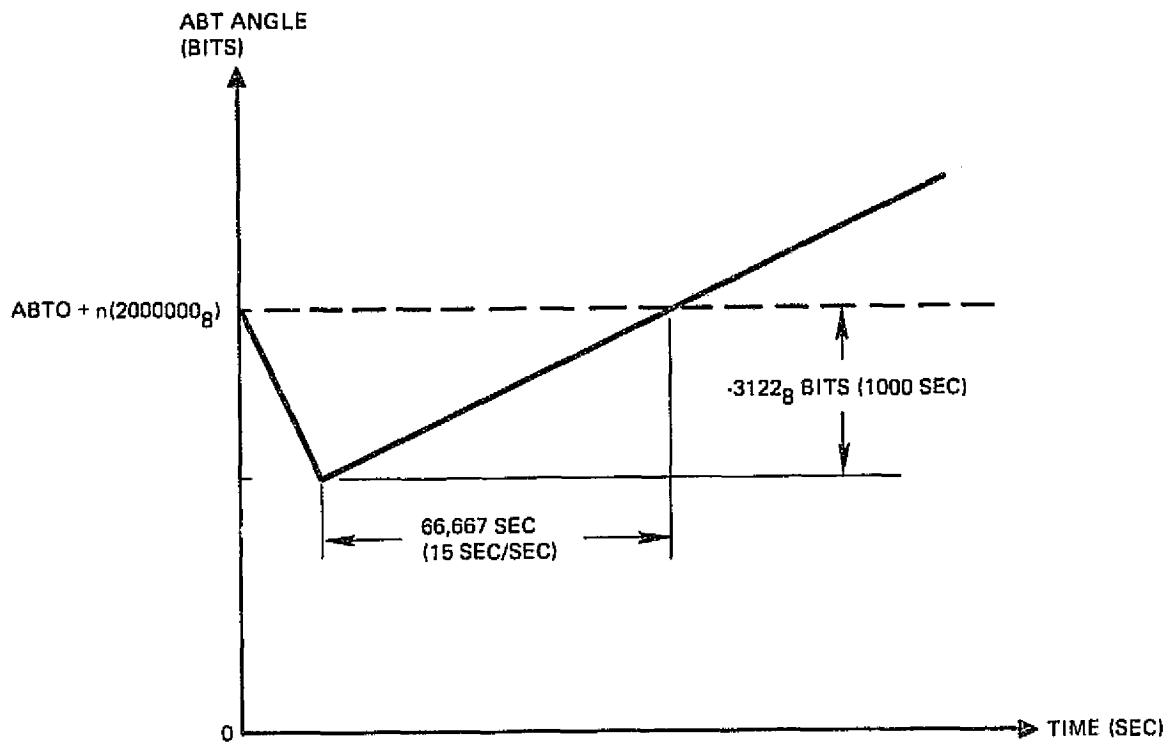


Figure 7-2. Ramp Function for the Gimbal Test

There were two submodes in GWEN:

RUNNING AVERAGES. This submode, when exercised, and depending on the main program mode, computed running averages of both AA/C axes, the gimbal readout, the GST x and y deflections, and the differences between the star tracker x deflection and table angle. The last computed running average for all but the latter signal, was stored for transmittal to magnetic tape upon exit from the submode. The running averages were each computed by the equation:

$$\bar{x}_{n+1} = (1 - e) \bar{x}_n + e y_{n+1}$$

where

\bar{x} = running average

y = observation

e = weighting factor

The details for each running average including scaling, update interval and weighting constant are given in Table 7-8.

DATA COLLECTION. The remarks for the submode in SUE apply.

7.2.2 Mode Control

The teletypewriter was used only to start and stop the program. All other control was from six manual switches on the DTU. The switch logic for mode control is shown in Table 7-5. The logic for star selection is shown in Table 7-6. Switch No. 3 controlled the RUNNING AVERAGES submode, and switch No. 4 the DATA COLLECTION submode. For all switches "up" corresponded to a "one" state which in turn corresponded to the affirmative state of the switch function name.

Table 7-5. GWEN Mode Control Logic

Mode	Description	Switch	
		No. 1 Bit 0*	No. 2 Bit 1*
1	REF POS	0	0
2	ZERO POS	0	1
3	STAR TRANSIT	1	1

*Slow input channel, status word bits

Table 7-6. GWEN Star Selection Logic

Star	n Value	Switch	
		No. 5 Bit 10*	No. 6* Bit 9
1	1	0	1
2	2	1	0
3	3	1	1

*Slow input channel, status word bits

7.2.3 Program Discrete Commands

The program sets the bits of the slow output channel, bilevel command word to the states indicated in Table 7-7. Bit 0, SEA TRACK/SEARCH commanded the GST to switch from the gimbal servo loop implemented about the gimbal readout and the computer to the loop using the star tracker vertical output signal. The former loop used the computer to supply a nominal star position and a summing junction; the latter was implemented entirely in the GST electronics. Since it was desired to switch to the tracker loop as soon as a star is acquired, bit 0 was made identical to bit 4 of the slow input channel status word, GST TRACK/SEARCH.

Table 7-7. GWEN Discrete Commands

Slow Output Channel Command Word		Mode		
Bit	Description	1	2	3
0	SEA TRACK/SEARCH	0	0,1	0,1
1	SEA MOTOR INHIBIT	0	0	0
2	GST SEARCH	0	0	0
3	GST BOS INHIBIT	0	0	0
4	SST SEARCH	0	0	0
5	ABT INTEGRATOR INHIBIT	0	0	0
6	ABT MOTOR INHIBIT	0	0	0
7	SPARE	0	0	0
↓	+			
15	SPARE	0	0	0

7.2.4 Real Time Diagnostic Data

Key signals were sent to the 8 channel stripchart recorder via the CDC 1700 DACs for display during the test. In addition the memory "peek," a LED display on the VTU of selected words in the 1700 memory, was used to display the running average of the gimbal readout angle. The

signals displayed are described in Table 7-8. The description of the DATA REAL TIME DISPLAY for SUE in the previous section applies to GWEN except for the weighting constants, e, and the equation for ERROR which, for GWEN, was:

$$\text{ERROR} = \frac{\text{GSTX}}{6.7} - (0.618)(\text{ABTA}-\text{ABTO})$$

where GSTX is the GST x deflection in millivolts and (ABTA-ABTO) is the difference between the ABT angle and its nominal angle for each star in counts.

Table 7-8. GWEN Real Time Display

	DAC Channel			Update Interval	Scaling		Output Display Maximum	Running Average e			
	Mode				Input Signal	Output Display					
	1	2	3								
AGRAX	4	4	4	100 sec	Direct	0.1V/cnt	20,000 cnts	--			
AGRAY	5	5	5	100 sec	Direct	0.1V/cnt	20,000 cnts	--			
AGRAZ	6	6	6	100 sec	Direct	0.1V/cnt	20,000 cnts	--			
GSTX	7			50 msec	6.7 mV/sec	0.25V/sec	40 sec	0.0125			
GSTY	8			50 msec	6.7 mV/sec	0.25V/sec	40 sec	0.0125			
AA/CX	9	9		1 sec	0.15V/sec	0.25V/sec	40 sec	0.05			
AA/CY	10	10		1 sec	0.15V/sec	0.25V/sec	40 sec	0.05			
ERROR			11	50 msec	(see text)	0.25V/sec	200 sec	0.05			
GSTA	on DTU			50 msec	digital display		full	0.05			

7.2.5 Data Collection

Collection of data on magnetic tape in the V73 computer was initiated and terminated by switch No. 4 on the DTU panel. There were three data formats:

- 1) Non-track
- 2) Start of track
- 3) Track.

Three conditions were necessary for the track state: 1) MODE 3; 2) a track signal from the GST (SI channel STATUS word, bit 4); and 3) a positive ramp be present. During the nontrack state three time-tagged gyro signals were stored on tape every one second:

GRAX = x gyro angle, arc seconds

GRAY = y gyro angle, arc seconds

GRAZ = z gyro angle, arc seconds.

At the start of track, running averages calculated and stored during MODE 1 and MODE 2 were stored on tape:

GSTA = Last average gimbal angle calculated in MODE 2 before switch No. 3 was turned off, arc seconds

GSTX = Last average star tracker horizontal angle calculated in MODE 2 before switch No. 3 was turned off, arc seconds

GSTY = (Same as GSTX, but for vertical angle)

ΔAA/CX = Last average AA/C horizontal angle calculated in MODE 2 before switch No. 3 was turned off minus the last average AA/C horizontal angle calculated in MODE 1 before switch No. 3 was turned off, arc seconds

ΔAA/CY = (Same as AA/CX, but for vertical angle).

During track, time tagged information from the gyros, the GST, and the ABT were stored every one second:

GRAX = (see above)

GRAY = (see above)

GRAZ = (see above)

GSTA = Gimbal angle, arc second

GSTX = Star tracker horizontal angle, arc seconds

GSTY = Star tracker vertical angle, arc seconds

ABTA = ABT angle with zero corresponding to the GST horizontal boresight position, arc seconds.

Time tags were accurate to 1 msec. Scaling for the signals corresponded to Table 7-8. Angles in arc seconds were given to one significant place.

8. PADS PERFORMANCE EVALUATION PROGRAMS

The performance evaluation of the PADS test data was performed offline on a CDC 6500 digital computer via a timeshare terminal. The offline computer programs were coded in FORTRAN. Their input consisted of the magnetic tape data from the V73 computer and certain initialization and control parameters which were inserted from the timeshare terminal. Their output consisted of the three-axis attitude errors in the PADS estimate of its inertial attitude plus other data which facilitated interpretation of the attitude errors. Two offline programs were used: one for the strapdown tests, and one for the gimbal tests.

A functional block diagram applicable to either computer program is shown in Figure 8-1. The program is divided into two main sections: 1) the PADS algorithms, and 2) the laboratory algorithms. In the ground-fixed test configuration the PADS axes are identical to the laboratory axes, and are physically defined by the optical cube on the strapdown star tracker, or the three reference mirrors on the gimbal star tracker. The PADS algorithms estimate the attitude of the PADS axes relative to their inertial attitude at the start of the test run. In a four hour test, for example, the PADS axes will rotate 60° due to the rotation of the earth. The orthogonal transformation matrix \hat{A} will reflect the PADS estimation of the rotation given continuous gyro information and periodic star tracker transits. The laboratory algorithms compute the true inertial attitude of the laboratory, expressed by the matrix A, using the precisely known value of earth rate. The agreement between these two matrices is a direct measure of the PADS performance.

The PADS algorithms are identical to those described in Section 3.2 with the exception of the star catalog information. In the laboratory test the star catalog information is formed by the laboratory algorithms. These algorithms compute the orientation of the collimated star beams relative to the true laboratory or PADS axes.

In addition to the two main sections the computer programs also contain data formatting and attitude error generation algorithms. The latter determine the small angle three-axis attitude errors from the nondiagonal elements of the matrix product $\hat{A} A^T$.

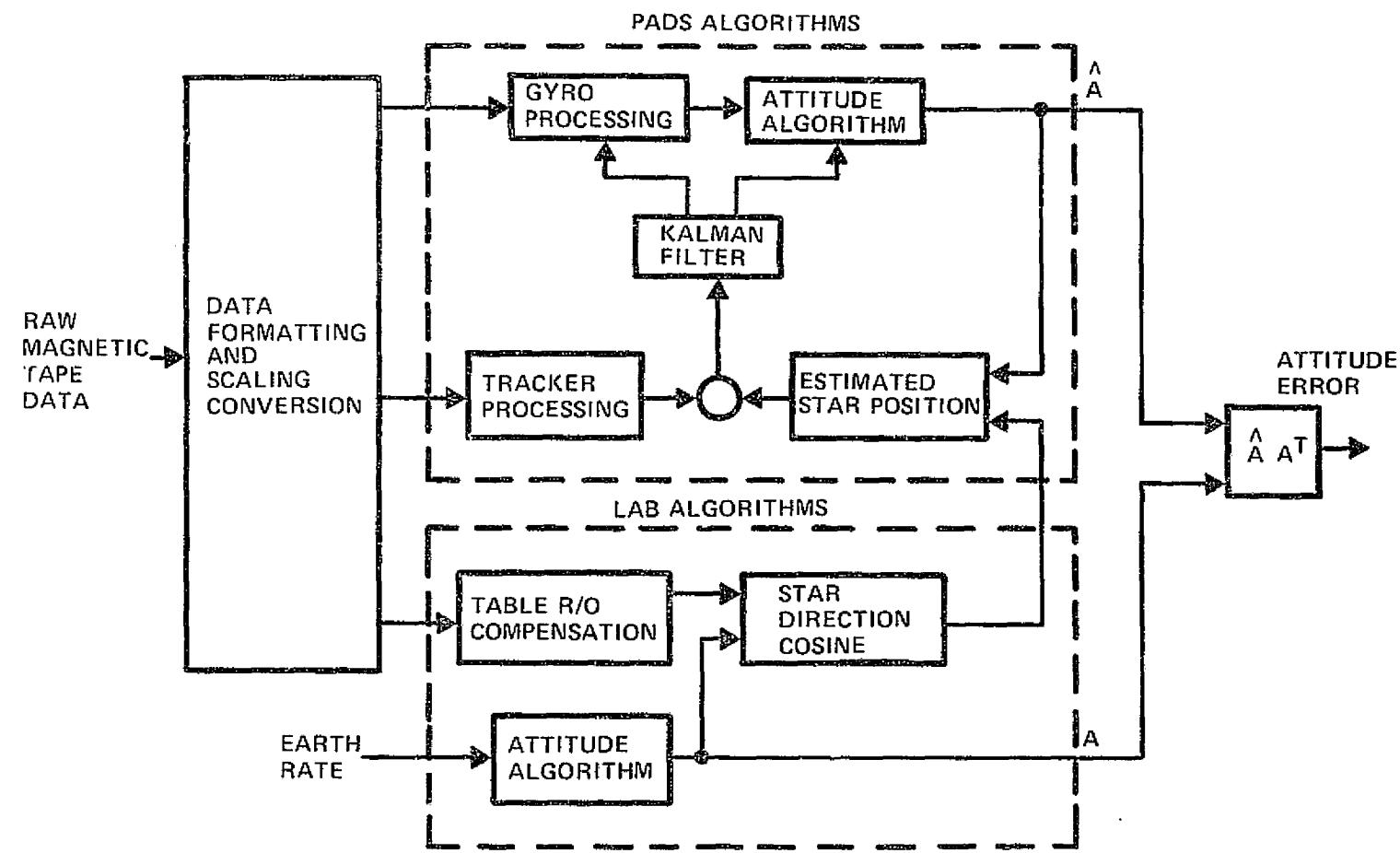


Figure 8-1. PADS Offline Data Evaluation Program

The derivation of the fundamental equations for the offline computer programs is given in Reference 7. Specific comments regarding the application of these equations to the PADS strapdown and gimbal system tests are given in the following sections.

8.1 STRAPDOWN SYSTEM DESCRIPTION

8.1.1 True Laboratory Attitude

The laboratory configuration of the PADS subsystem is illustrated in Figure 8-2. The SST optical cube defines both the PADS and the laboratory axes. The orientation of this optical cube can be described by a right-handed, orthogonal coordinate set (x_1, x_2, x_3) in which each axis is normal to a cube face as in Figure 8-2. To definitize this coordinate set \bar{x}_3 is taken to point opposite the gravity vector, and \bar{x}_1 is selected such that it experiences no component of the earth's angular velocity, $\bar{\omega}_e$, i.e., $\bar{\omega}_e \cdot \bar{x}_1 = 0$. The optical cube with its above defined coordinate set is thus taken to be the laboratory reference, and the term "laboratory attitude" will be taken to mean the orientation of the axes (x_1, x_2, x_3) relative to an inertial set (z_1, z_2, z_3) . This latter set of axes will be taken to be identical to axes (x_1, x_2, x_3) at the start of any particular subsystem test run. The laboratory attitude at any subsequent run time is then given by

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = A_{xz}(t) \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (8-1)$$

where

$$A_{xz}(t) = \begin{bmatrix} 1 - \beta(\lambda_2^2 + \lambda_3^2) & \alpha\lambda_3 + \beta\lambda_1\lambda_2 & -\alpha\lambda_2 + \beta\lambda_1\lambda_3 \\ -\alpha\lambda_3 + \beta\lambda_1\lambda_2 & 1 - \beta(\lambda_1^2 + \lambda_3^2) & \alpha\lambda_1 + \beta\lambda_2\lambda_3 \\ \alpha\lambda_2 + \beta\lambda_1\lambda_2 & -\alpha\lambda_1 + \beta\lambda_2\lambda_3 & 1 - \beta(\lambda_1^2 + \lambda_2^2) \end{bmatrix} \quad (8-2)$$

$$\lambda_i = \frac{\bar{\omega}_e \cdot \bar{x}_i}{\bar{\omega}_e} \quad i = 1, 2, 3 \quad (8-3)$$

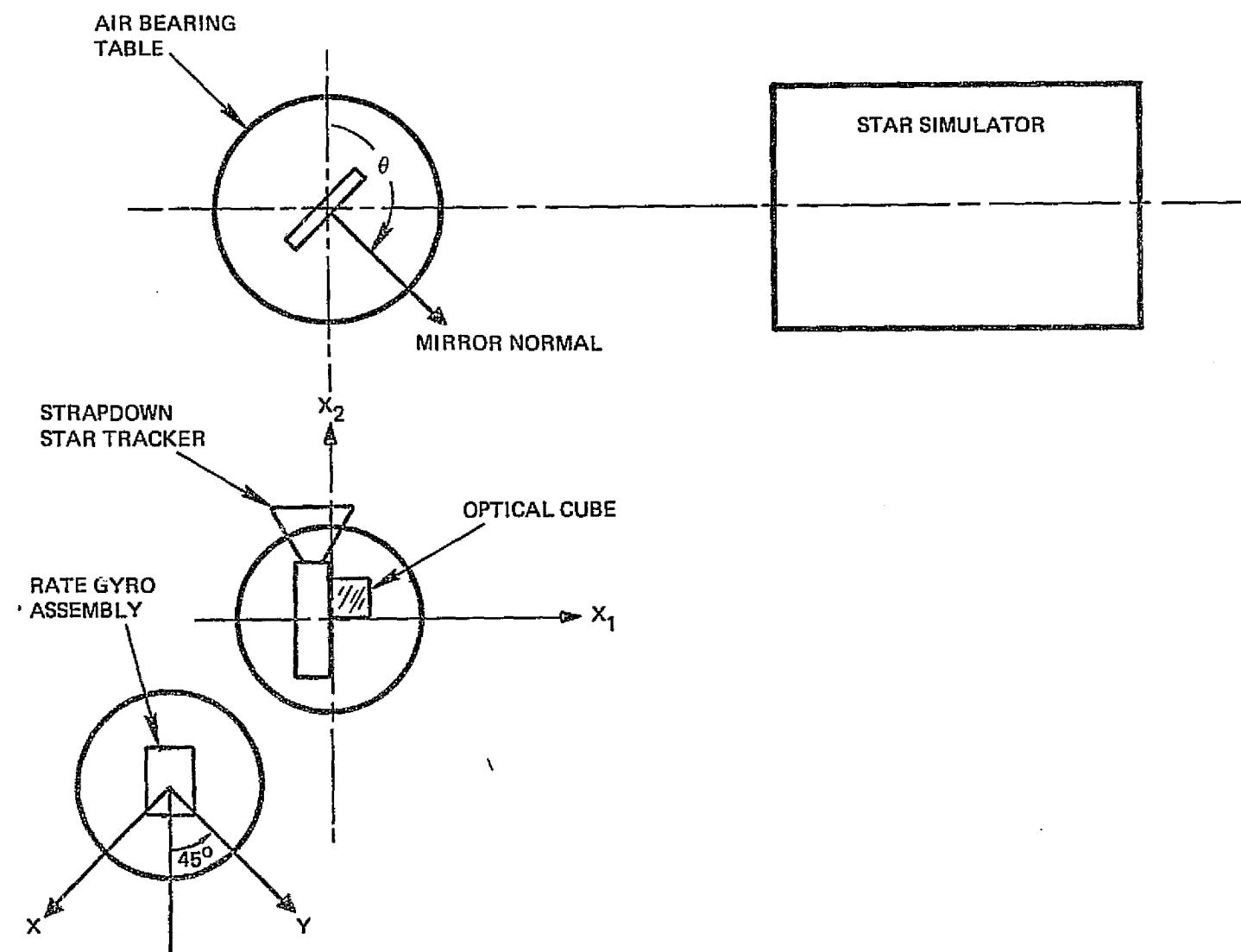


Figure 8-2. PADS Laboratory Setup

$$\alpha = \sin \omega_e t ; \quad \omega_e = |\bar{\omega}_e| \quad (8-4)$$

$$\beta = 1 - \cos \omega_e t \quad (8-5)$$

The λ_i depend, of course, upon the orientation of the laboratory relative to the earth rate, $\bar{\omega}_e$. This is largely a function of its latitude, taken to be 33.90323 deg north. It should be mentioned that inaccuracies in this figure (or in the alignment of the optical cube), while influencing the true knowledge of $A_{xz}(t)$ will have no bearing upon the subsystem performance measure, as the estimated laboratory attitude provided by PADS will contain exactly the same effect. This will be discussed more fully in Section 8.1.2.

8.1.2 PADS Estimate of the Laboratory Attitude

The PADS subsystem must estimate the laboratory attitude without being privy to latitude and a priori earth rate information. The SST/optical cube alignment is such that the tracker's boresight lies along \bar{x}_2 , with its azimuth and elevation outputs occurring, respectively, about x_3 and x_1 . Now the actual orientation of (x_1, x_2, x_3) relative to (z_1, z_2, z_3) is unknown to the PADS subsystem, as this information can only be established through knowledge of ω_e , latitude, and run time, t . Thus PADS can only provide estimates of the x_i , say \hat{x}_i , by effective use of the SST and IRU. The PADS output is then an estimated laboratory attitude matrix, $\hat{A}_{xz}(t)$, defined by

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} = \hat{A}_{xz}(t) \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (8-6)$$

Combining Equations (8-1) and (8-6)

$$\begin{bmatrix} \hat{x}_1 \\ \hat{x}_2 \\ \hat{x}_3 \end{bmatrix} = \hat{A}_{xz}(t) A_{xz}^{-1}(t) \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (8-7)$$

The degree to which $\hat{A}_{xz} A_{xz}^{-1}$ matches the identity matrix is a direct measure of the effectiveness of the PADS subsystem as an attitude estimator.

To be effective as a three-axis attitude estimator, the SST must be sensitive to attitude motions about each of its three axes. A single PADS tracker fails in this respect due to its extremely small field-of-view, and thus a complete PADS subsystem must employ two such trackers, with optical boresights separated by more than 30 deg or so. Since the laboratory test involved only a single tracker, the system prediction of attitude about the x_2 axis will be ignored, and performance measured solely upon its success in pointing the x_2 axis. In essence, the system will thus be treated as a two-axis estimator.

This two-axis estimator employs a three-axis gyro package, whose gyro input axes (x , y , z) are illustrated by Figure 8-2 and satisfy

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} -.707 & -.707 & 0 \\ .707 & -.707 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (8-8)$$

Unfortunately, the gyro whose input axis is z (or x_3) is much poorer in performance than the other two, and thus causes very pessimistic predictions of laboratory attitude about the x_3 axis. In fact, such results can be termed Worst Case. Best Case results would be obtained if the z gyro were aligned, instead, along the x_2 axis, whose attitude is not effectively estimated anyway. Thus two types of performance results will be presented in Section 9. Worst case results will deal with the actual laboratory gyro configuration given by Equation (8-8), and best case results will simply transform the actual gyro outputs to the values that they would have experienced had the z gyro been aligned along x_2 . The only assumption made in this process is that the gyro errors are invariant to rotation, an assumption that is not really germane to the evaluation of the PADS.

8.1.3 The Star Catalog

The PADS estimation algorithm has been previously described in Section 3.2. Key to its operation is its usage of fixed star locations as

attitude benchmarks in an inertial reference frame. In analogy, the location of comparable stars in the inertial set (z_1 , z_2 , z_3) must be established. This effectively then becomes the estimator's star catalog.

Figure 8-2 illustrates the means whereby a star line of sight is formed using the star simulator and air bearing table mirror. A fixed separate light source for each of three stars is housed in the star simulator. The light emanating from the j^{th} such source is defined by

$$\bar{u}_s^j = \sum_{i=1}^3 u_{si}^j \bar{x}_i \quad (8-9)$$

where the u_{si}^j are time invariant. The table mirror normal, on the other hand is defined by

$$\bar{n} = \sin \theta(t) \bar{x}_1 + \cos \theta(t) \bar{x}_2 \quad (8-10)$$

The input star line-of-sight to the SST is then given by

$$\bar{u}^j = \sum_{i=1}^3 u_i^j \bar{x}_i = \bar{u}_s^j - 2 \bar{n} (\bar{n} \cdot \bar{u}_s^j) \quad (8-11)$$

The inertial coordinates of this star at time t , namely the benchmark attitude reference used by PADS, are then given by the three direction cosines

$$a_i^j = \bar{u}^j \cdot \bar{z}_i \quad i = 1, 2, 3 \quad (8-12)$$

where clearly

$$\begin{bmatrix} a_1^j \\ a_2^j \\ a_3^j \end{bmatrix} = A_{xz}^{-1} \begin{bmatrix} u_1^j \\ u_2^j \\ u_3^j \end{bmatrix} \quad (8-13)$$

The method whereby PADS causes \hat{A}_{xz} to converge toward A_{xz} is then basically dependent upon adjusting the attitude estimate until its estimate of the u_i^j , say \hat{u}_i^j , coincides with the u_i^j as obtained by measurement. Clearly

$$\begin{bmatrix} \hat{u}_1^j \\ \hat{u}_2^j \\ \hat{u}_3^j \end{bmatrix} = \hat{A}_{xz} \begin{bmatrix} a_1^j \\ a_2^j \\ a_3^j \end{bmatrix} \quad (8-14)$$

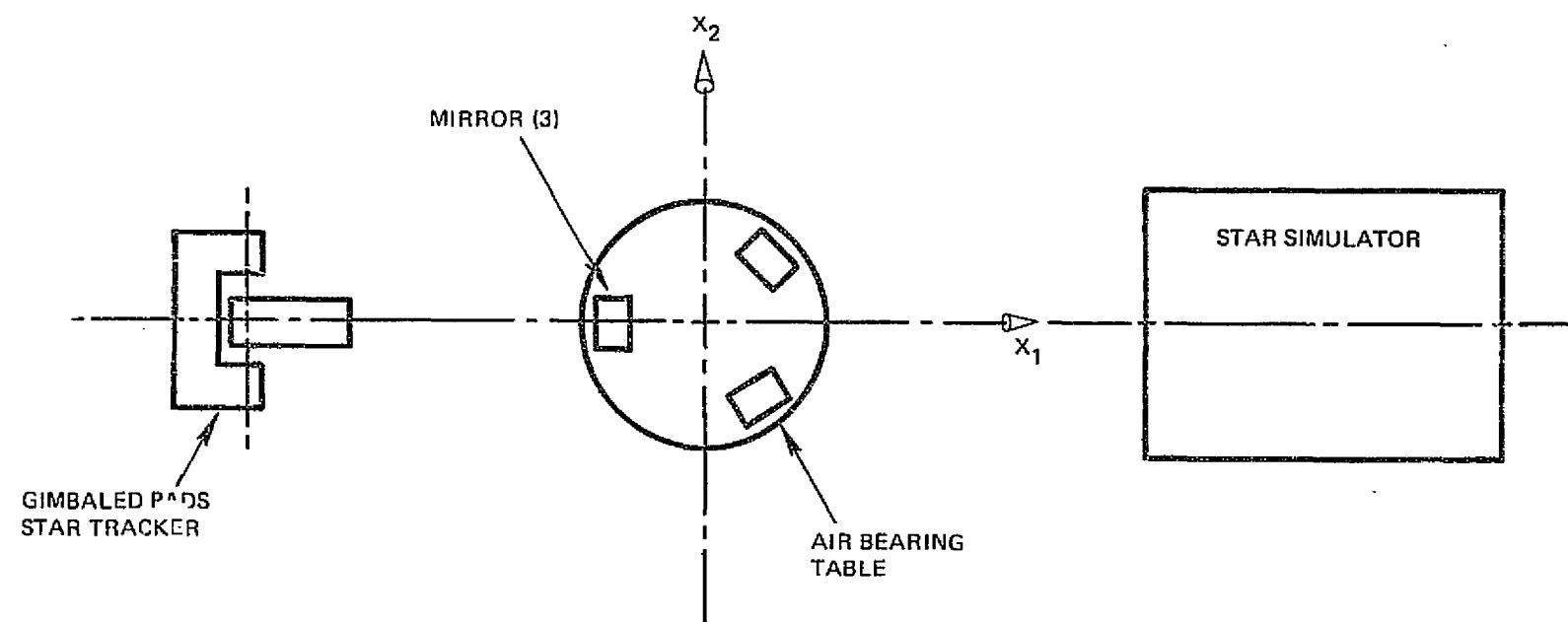
As mentioned before, errors in providing exact truth model earth rate or latitude data will influence A_{xz} , but not the PADS performance measure $\hat{A}_{xz} A_{xz}^{-1}$. This is because the same error effect will appear in \hat{A}_{xz} due to the fact that the inertial star direction cosines, a_i^j , are directly influenced by A_{xz} through Equation (8-13). Likewise, the apparent drift rates of the three gyros will shift slightly should inexact values of ω_e or latitude be used. A similar comment can be made should the gyros not precisely satisfy the transformation of Equation (8-8). In neither event is the performance measure of PADS degraded.

8.2 GIMBAL SYSTEM TEST

In parallel to the system test employing a body fixed tracker, the purpose of the gimbaled system test is to establish the performance of the gimbaled star tracker (SST) and the gyro assembly when combined with a suitable data reduction algorithm as an attitude estimation subsystem. This subsystem will be used to estimate the attitude of the laboratory relative to an inertial set of coordinates. As before, the true attitude of this earth-fixed laboratory is essentially known as a function of time, providing a direct means of evaluating system performance.

8.2.1 True Laboratory Attitude

The laboratory configuration of the PADS subsystem is illustrated in Figure 8-3. The laboratory fixed axes are defined as in Section 8.1; a right-handed, orthogonal, coordinate set for which x_3 is taken to point opposite the gravity vector, and x_1 is selected such that it experiences no component of the earth's angular velocity, $\bar{\omega}_e$, i.e., $\bar{\omega}_e \cdot \bar{x}_1 = 0$. The term "laboratory attitude" will be taken to mean the orientation of the axes (x_1, x_2, x_3) relative to an inertial set (z_1, z_2, z_3). This latter set of axes will be taken to be identical to axes (x_1, x_2, x_3) at the start of any particular subsystem test run. The laboratory attitude at any subsequent time is then given by Equations (8-1) to (8-5).



6-8

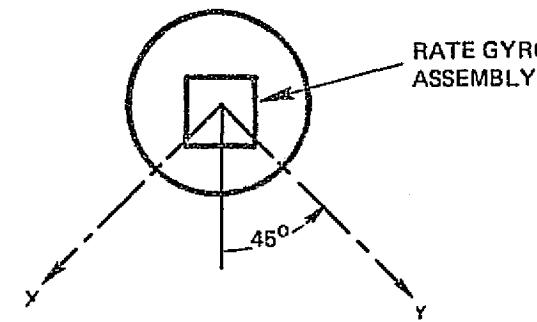


Figure 8-3. Gimbaled PADS Laboratory Setup

8.2.2 Gimbal PADS Estimate of the Laboratory Attitude

The PADS subsystem must estimate the laboratory attitude without being privy to latitude and a priori earth rate information.

Consequently, the actual orientation of (x_1, x_2, x_3) relative to (z_1, z_2, z_3) cannot be established by the PADS subsystem, as this information can only be obtained through knowledge of ω_e , latitude, and time, t . Thus PADS can only provide estimates of the x_i , say \hat{x}_i , by effective use of the GST and IRU data. The PADS output is then an estimated laboratory attitude matrix, $\hat{A}_{xz}(t)$, defined by Equation (8-6), with Equation (8-7) again providing a measure of the system's effectiveness.

Unlike the body fixed tracker, the gimbal star tracker provides attitude estimates about all three axes (rather than two axes). However, since the gimbal motion between the two outer laboratory "stars" is only about 38 deg, the anticipated accuracy about the x_1 axis is less than that about either x_1 or x_3 . Thus the results will be presented in two ways: as a full three-axis estimator, and as a two-axis estimator which ignores errors about x_1 . This latter figure of merit will provide a more direct comparison to the results obtained for the body fixed tracker. Also, since three-axis estimates are the primary goal of this test, there is no great advantage in any particular alignment of the IRU. Thus, the actual laboratory orientation of this unit given by Equation (8-8) will be assumed throughout the test runs.

8.2.3 The Star Catalog

The gimbal PADS estimation algorithm has been previously described in Section 3.2. Key to its operation is its usage of fixed star locations as attitude benchmarks in an inertial reference frame. In analogy, the location of comparable stars in the inertial set (z_1, z_2, z_3) must be established. This effectively then becomes the estimator's star catalog.

Figure 8-4 illustrates the means whereby a star line of sight is formed using the star simulator and air bearing table mirror. A single fixed light source emanates from the star simulator and is deflected downward along $-x_3$ by a fixed mirror mounted above the air bearing table. A tilted mirror mounted to the table top then deflects this light beam (when the table top is in position) toward the tracker. By utilizing the table mirrors, three such stars of differing elevation angles can be simulated. This establishes the direction cosines (in lab axes) of each star, and its equivalent inertial coordinates are then given, as before, by Equations (8-12) and (8-13). Likewise, estimates of the star direction cosines (in estimated lab axes) are given by Equation (8-14), and the comments following this equation apply here as well.

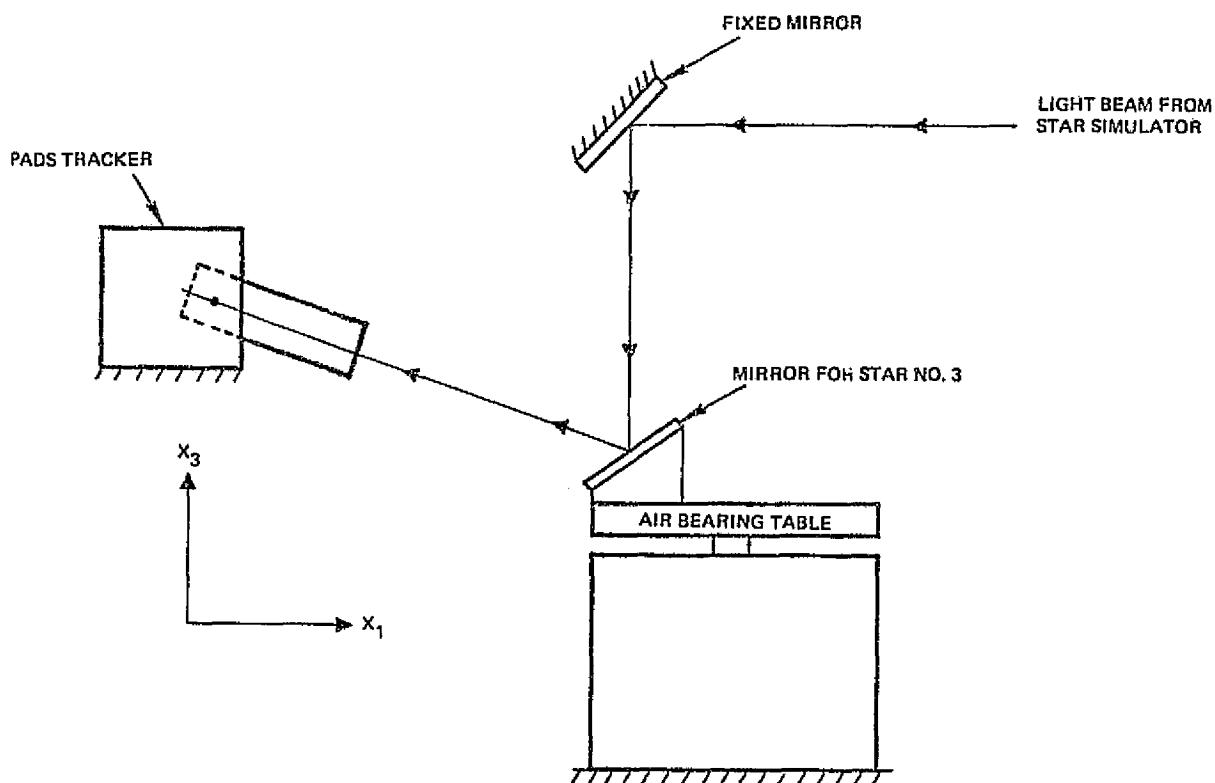


Figure 8-4. Establishing Star Line of Sights
for the Gimbaled Star Tracker

9. STRAPDOWN SYSTEM TEST

This section describes the strapdown system test which was run from 1 October 1975 to 10 October 1975. The orbit scenario on which the test was based is described along with comments regarding initial alignment of the PADS axes. All of the four test runs which were conducted during the ten day test period are analyzed using several performance measures. Two of the test runs were selected for detailed analysis to illustrate the effect of individual error sources on the PADS attitude estimates. A parametric analysis is made to evaluate the effect of star update interval on the PADS accuracy. Lastly, a summary of the PADS accuracy is presented.

9.1 TEST DESCRIPTION

The spacecraft configuration postulated for the PADS system test is that of a three-axis stabilized, earth-pointed satellite in geosynchronous orbit. An experiment on board, a telescope, for example, requires precise information regarding the inertial attitude of its sensitive axis or axes. The PADS is used to provide this information.

A calibration of the PADS star tracker boresight axis relative to the experiment axes is allowed once every ten days. Following a calibration the experiment may require the PADS attitude information for any length of time, for any number of times, during the next ten days.

By way of configuring a practical laboratory test, four test runs, nearly evenly spaced in time, were conducted during a ten day test period. Each run was four hours in duration. During each run a star update was made every 20 minutes. This corresponded to a star being available every 5° in right ascension. Three different star declinations were used. All stars were $8 M_V$ GO ($6000^{\circ}K$).

The test period was limited to ten days by the scope of the PADS contract and not by any limitation in the stability of the star tracker. Four runs during the ten day period were adequate to measure the day-to-day stability of the tracker, while a four hour run was sufficient to ensure steady-state behavior for star updates up to 60 minutes apart. The minimum star update time of 20 minutes was determined by the gyro performance (see Section 4.1). Three star declinations were considered adequate to exercise

the tracker field of view linearity accuracy. Making all stars 8 M_V presented a worst case situation in terms of tracker noise and simplified test equipment design.

9.2 INITIAL ALIGNMENT/CALIBRATION

The PADS reference axes were defined physically by the optical cube on the strapdown star tracker. The PADS experienced a fixed input rate, i.e., earth rate, during a test run. Consequently, no effort was made to precisely determine the gyro input axes orientations relative to the cube since an axis misalignment would be indistinguishable from a fixed drift rate error.

The original intent was to align the tracker electro-optical boresight to the normal to the front face of the optical cube, and to adjust the field of view alignment about the boresight so that a zero vertical output resulted for a star on the negative x axis at the edge of the field of view. The field of view nonlinearities were to be calibrated from a component test performed in a separate facility from that of the system test.

Unfortunately, the calibration data from the star tracker component test contained unacceptable errors which were not recognized at the time the data was collected. These errors are described in Volume I, Section 7. As a result it was necessary to recalibrate the field of view using the three stars in the system test configuration. This recalibration took place immediately prior to the ten day system test. The overall result was the invalidation of the independent measure of the accuracy of the field of view linearity. The recalibration did not affect the basis for the alignment, albeit indirect, of the boresight to the optical cube, namely, the ground-rule that the boresight would be calibrated relative to the experiment axes every ten days.

9.3 SYSTEM TEST RESULTS

The following system test results were obtained using the computer performance evaluation programs described in Section 8.

9.3.1 Pass Parameters

Four test runs, each of approximately four hours in duration, were conducted between 1 October 1975 and 10 October 1975. This time tagged sensor data was then utilized by the Estimation Algorithm to predict both laboratory attitude and the gyro drift rates. Aside from the time tagged sensor data, the algorithm requires a number of additional inputs dealing primarily with statistical quantities that describe initial uncertainties in both attitude and gyro drift rates, as well as uncertainties in both gyro and star tracker noise parameters. In general, the attitude estimation performance of the Estimation Algorithm is dependent upon the values of assumed noise. Also of significance is the degree of filtering applied to the output of the tracker, as longer time constants tend to reduce the impact of tracker noise. Taking such parameter variations into account, a total of 31 attitude estimation computer passes were made based upon the four test runs previously mentioned. Table 9-1 lists the conditions for these 31 passes.

9.3.2 Performance Measures

The effectiveness of the Attitude Estimator is based primarily upon three things:

- 1) The degree to which the estimator accurately predicts the attitude of the x_2 axis. If θ_1 and θ_3 represent the estimation errors about, respectively, the x_1 and x_3 axis, then the boresight (x_2) attitude error is given by

$$\theta = \sqrt{\theta_1^2 + \theta_3^2} \quad (9-1)$$

- 2) The degree to which the boresight attitude error, which of course is unknown operationally, is reflected by the estimator's error covariance prediction. Observation of the latter should give a strong indication of the actual errors. Comparing the attitude error covariance prediction with the SST measurement residuals will check estimator "consistency."
- 3) The speed with which the attitude estimates converge from sizeable initial estimation errors (e.g., 100 sec) to errors that are close to "steady state."

Table 9-1. Conditions and Parameters of Computer Passes

Pass Conditions

Run Duration - 14800 sec

Star Update Interval - 20 min/40 min/60 min*

Each star utilized 3 times at 55 sec intervals

Gyro Orientation - Best Case/Worst Case*

Initial Conditions

Initial Attitude Estimate - 100 $\widehat{\text{sec}}$ error about x_1 and x_3

Initial Attitude Uncertainty (1σ) 100 sec about x_1 and x_3 ; 10 $\widehat{\text{sec}}$ about x_2

Initial gyro drift rate uncertainty - .02 $\widehat{\text{sec/sec}}$

Sensor Parameters

Gyro:

Estimated Drift Rates. Gyro x -.833 $\widehat{\text{sec/sec}}$
y -.478 $\widehat{\text{sec/sec}}$
z -1.055 $\widehat{\text{sec/sec}}$

Gyro noise σ_v - .02 to .08 $\widehat{\text{sec}}/(\text{sec})^{1/2}$ *

Gyro noise σ_u - $.2 \times 10^{-4}$ to $.6 \times 10^{-4}$ $\widehat{\text{sec}}/(\text{sec})^{3/2}$ *

Gyro noise σ_e - 0.1 $\widehat{\text{sec}}$

Star Tracker:

Calibration coefficients as specified in Volume I, Section 7

Time constant (both axes) - .0466 sec

Digital output filter (both axes) - 0 to 3 sec*

Output noise (both axes) - 1.5 to 3 $\widehat{\text{sec}}$ *

* Specified in Test Run

Items 1) and 2) are time variant and require additional qualification if clear figures of merit are to be adopted. Figure 9-1 illustrates a typical sequence of θ values, a value being plotted every 300 sec and also at times just prior and just subsequent to an attitude update.

For the merit figures, the discrete points are connected by straight lines. The mean pointing error and its standard deviation are then computed as

$$\mu_{\theta} = \frac{1}{(t_N - t_n)} \sum_{i=n}^N \frac{1}{2} (\check{\theta}_{i+1} + \tilde{\theta}_i) (t_{i+1} - t_i) \quad (9-2)$$

$$\sigma_{\theta} = \left\{ \frac{1}{(t_N - t_n)} \sum_{i=n}^N \frac{1}{3} \left[\check{\theta}_{i+1}^2 + \check{\theta}_i^2 + \tilde{\theta}_{i+1} \check{\theta}_i \right] (t_{i+1} - t_i) \right\}^{1/2} \quad (9-3)$$

where

$$\tilde{\theta}_i = \theta(t_i +) \quad (9-4)$$

$$\check{\theta}_i = \theta(t_i -) \quad (9-5)$$

with t_N and t_n representing, respectively, the final time and time at which the effect of initial estimates have disappeared. A similar approach is also used in computing the mean and standard deviation, μ_y and σ_y , of the attitude estimator's guess (based upon its covariance matrix) as to the reliability of its output. Lastly, μ_y and σ_y have similar interpretations regarding the measurement residual. The six merit figures will be used extensively in what follows.

9.3.3 Detailed Analyses of Passes No. 8 and No. 9

Pass No. 8 met the general conditions of Table 9-1 under the additional specifications:

Tracker noise (1σ) - 1.5 sec

Tracker output filter time constant - 3 sec

Tracker update interval - 20 min

Gyro noise σ_v - .04 sec/sec^{1/2} in x and y; .08 in z

σ_u - $.6 \times 10^{-4}$ sec/sec^{3/2} in x, y, and z

Gyro Orientation - Best Case

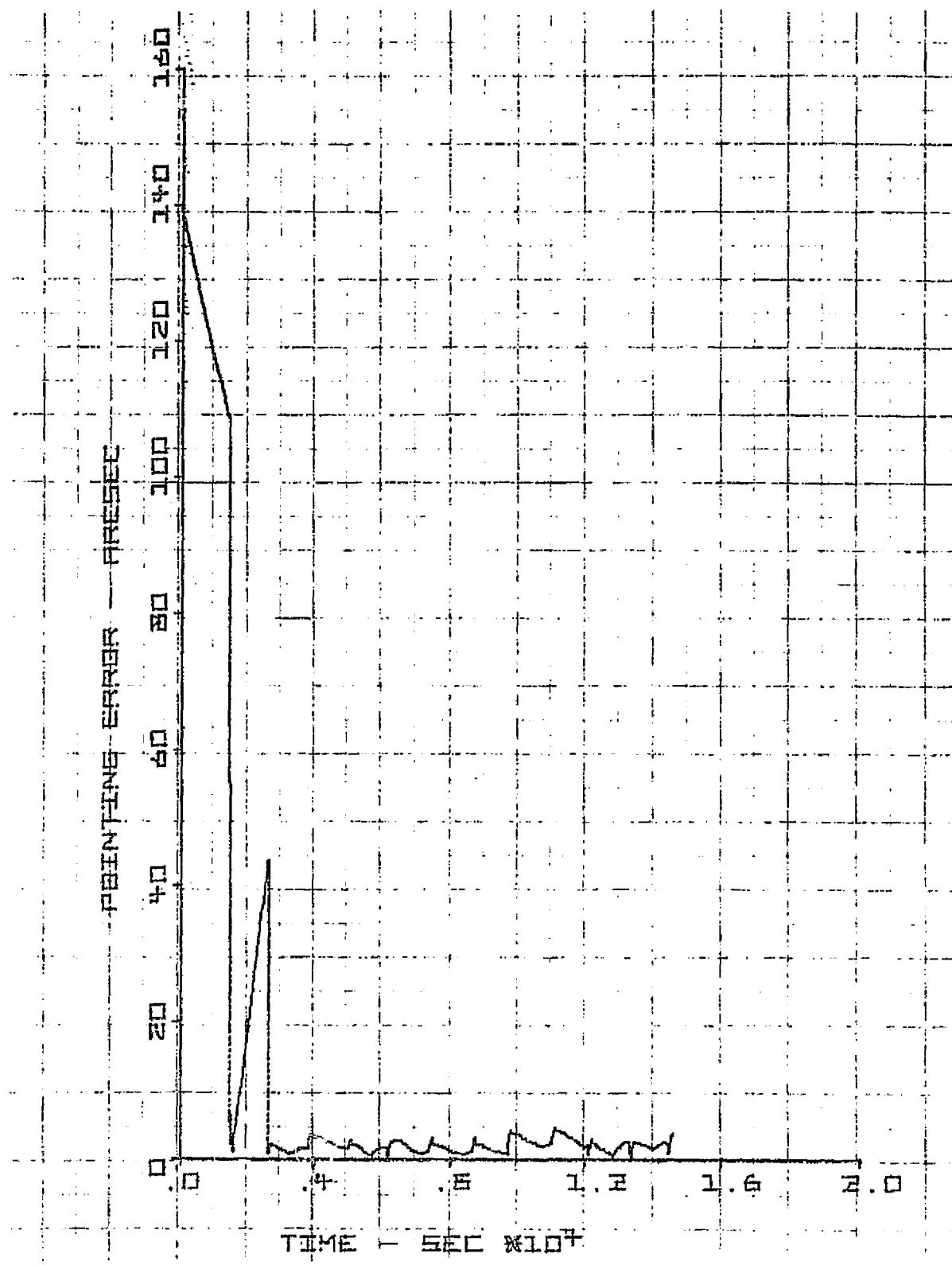


Figure 9-1. Pass No. 8

Figure 9-1 illustrates the convergence of the estimation error, θ , of the boresight (x_2) attitude. A dramatic correction in attitude estimation error is made after just one star sighting. However, the gyro drift rates retain sufficient error to cause considerable divergence until the second star sighting at about 2600 sec. The drift rates are then also corrected and fairly benign performance (which we shall call "steady state") occurs thereafter. Figure 9-2 illustrates, on a larger scale, the estimation error from about 5000 sec onward. An average pointing error of about $2 \frac{1}{2}$ sec is experienced, which corresponds to a 1.4 sec error per axis.

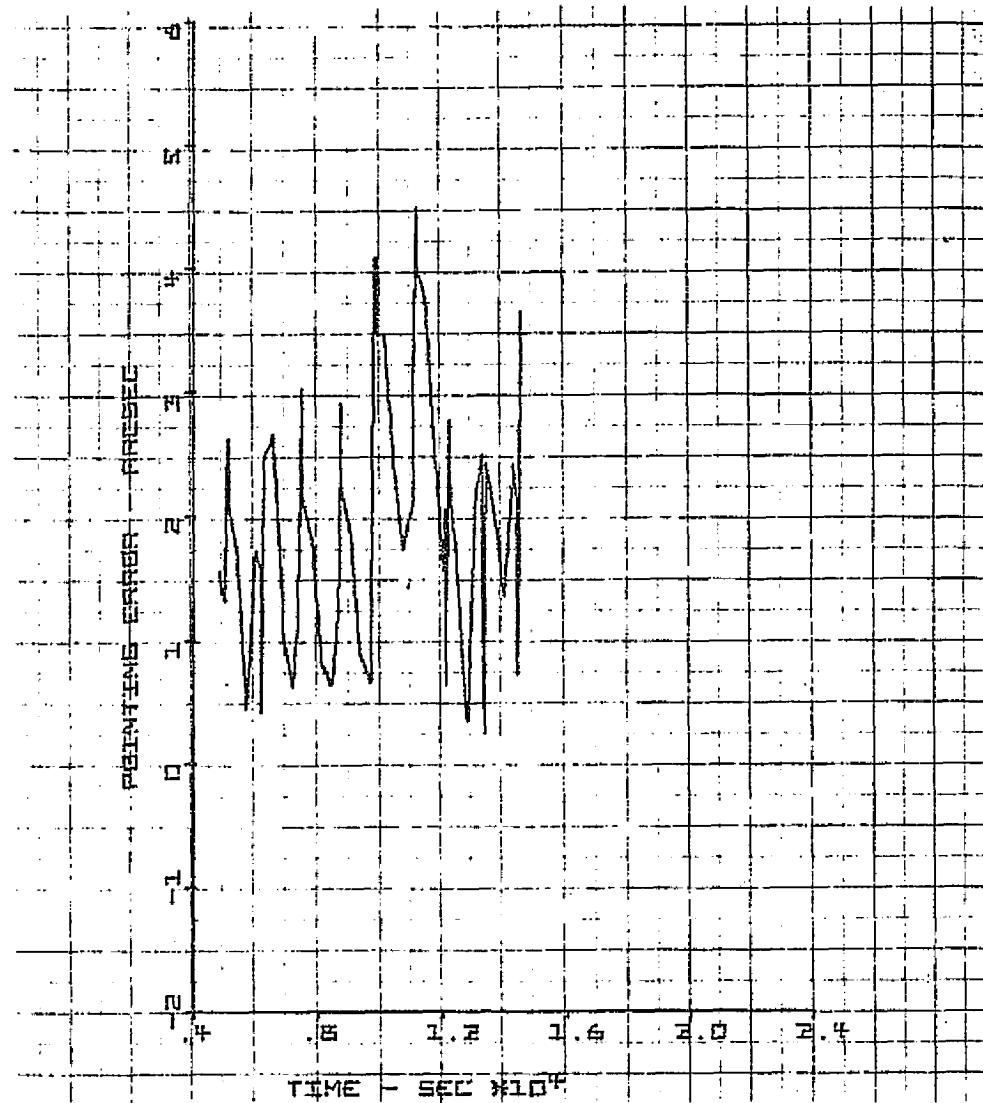


Figure 9-2. Pass No. 8 Expanded

When the conditions of Pass No. 8 are altered by assuming a worst case rather than best case gyro orientation, the convergence of θ remains about the same. Steady state behavior is considerably degraded, however, as Pass No. 9 in Figure 9-3 clearly shows. In this case an average pointing error of about 3.2 sec is evident, corresponding to 2.3 sec per axis. This is clearly a result of the z gyro drift rate fluctuation, which now directly influences the pointing estimate. If $\omega_g(t)$ represents a gyro's rate output, then Figure 9-4 presents the rate variation $\omega'_g(t)$ for each of the three gyros over the run duration $[0, T]$ where $T = 14800$ sec. $\omega'_g(t)$ is of the form

$$\omega'_g(t) = \omega_g(t) - \bar{\omega}_g(t) \quad (9-6)$$

where

$\bar{\omega}_g(t)$ is the average drift rate for the run duration.

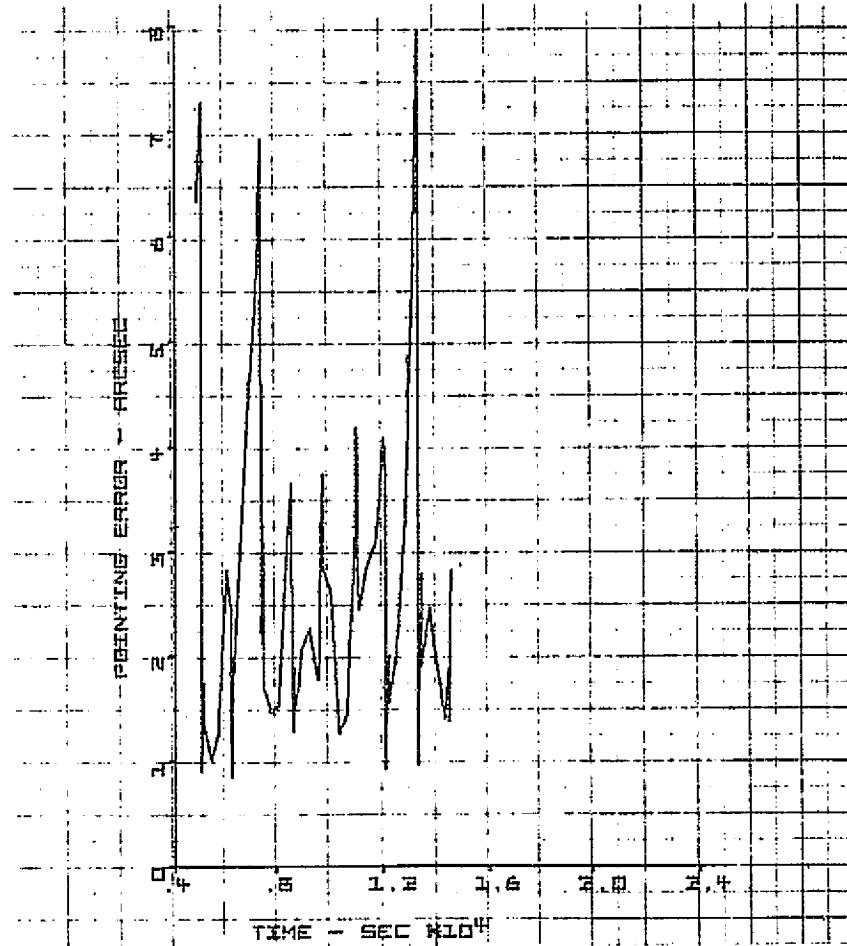


Figure 9-3. Pass No. 9

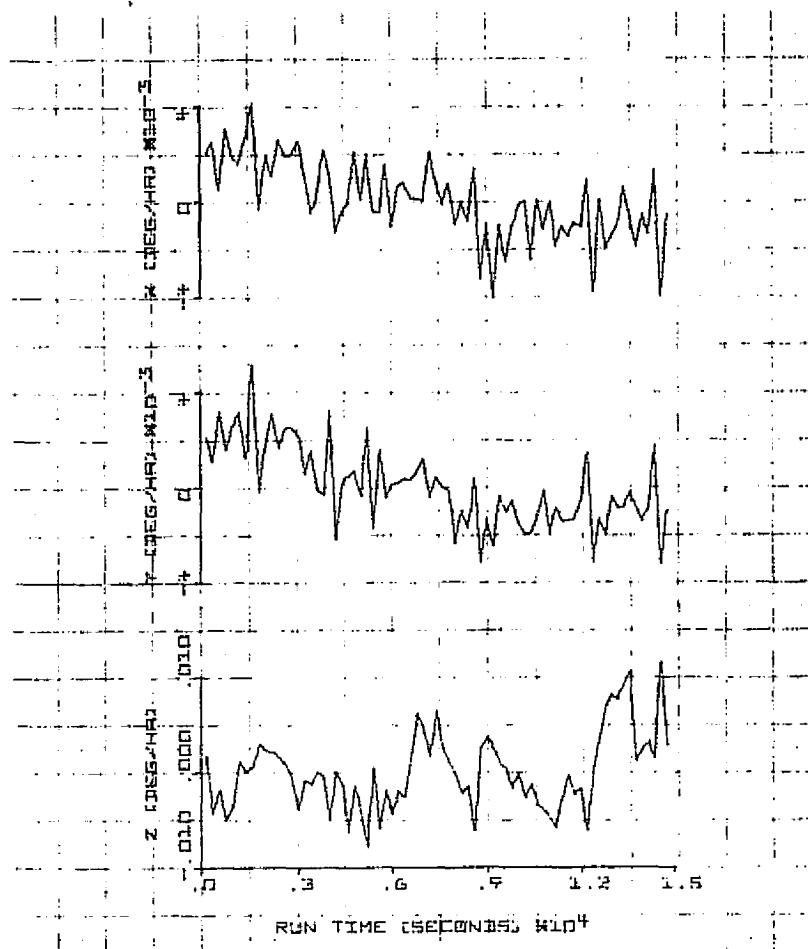


Figure 9-4. 10/10/75 Run (200 Sec/Sample)

It is clear that the z gyro experiences severe drift rate changes at both 6100 sec and 12730 sec. This is consistent with the results of Figure 9-3, which shows the start of a severe fluctuation in the attitude estimate at about these times.

9.3.4 PADS Steady State Parametric Test Results

The results for all four test runs are shown in Figure 9-5, in terms of the previously defined performance criteria μ_θ , σ_θ , $\hat{\mu}_\theta$, $\hat{\sigma}_\theta$, μ_y , σ_y . In general, the system results are excellent, with the following conclusions evident

- All of the 13 passes indicate an RMS pointing error, σ_θ , of better than 4 sec. In fact, the average σ_θ over the 13 passes is 3.08 sec for a per axis error of 2.2 sec.
- The performance of the best gyro orientation exceeds that for the worst orientation by 0.4 - 1.0 sec.
- Filtering the tracker output through a 3 sec time constant filter shows significant improvement over a 1 sec filter.

- Gyro data base B results in filter covariance estimates that agree more closely than A with actual performance.
- Passes 5, 6, 8, 17, 23, and 18 show excellent agreement between actual performance, filter predicted performance, and the actual measurement residuals.
- Passes 1, 7, 28, and 16 indicate poorer agreement. In Passes 1 and 7 too high a value of tracker noise was assumed. Pass 28 is plagued by tracker bias, which was independently established. Pass 16 is also somewhat plagued by such bias, but in addition is optimistic in its assessment of gyro noise.

Figure 9-5. PADS Test Results - 20 Min. Updates

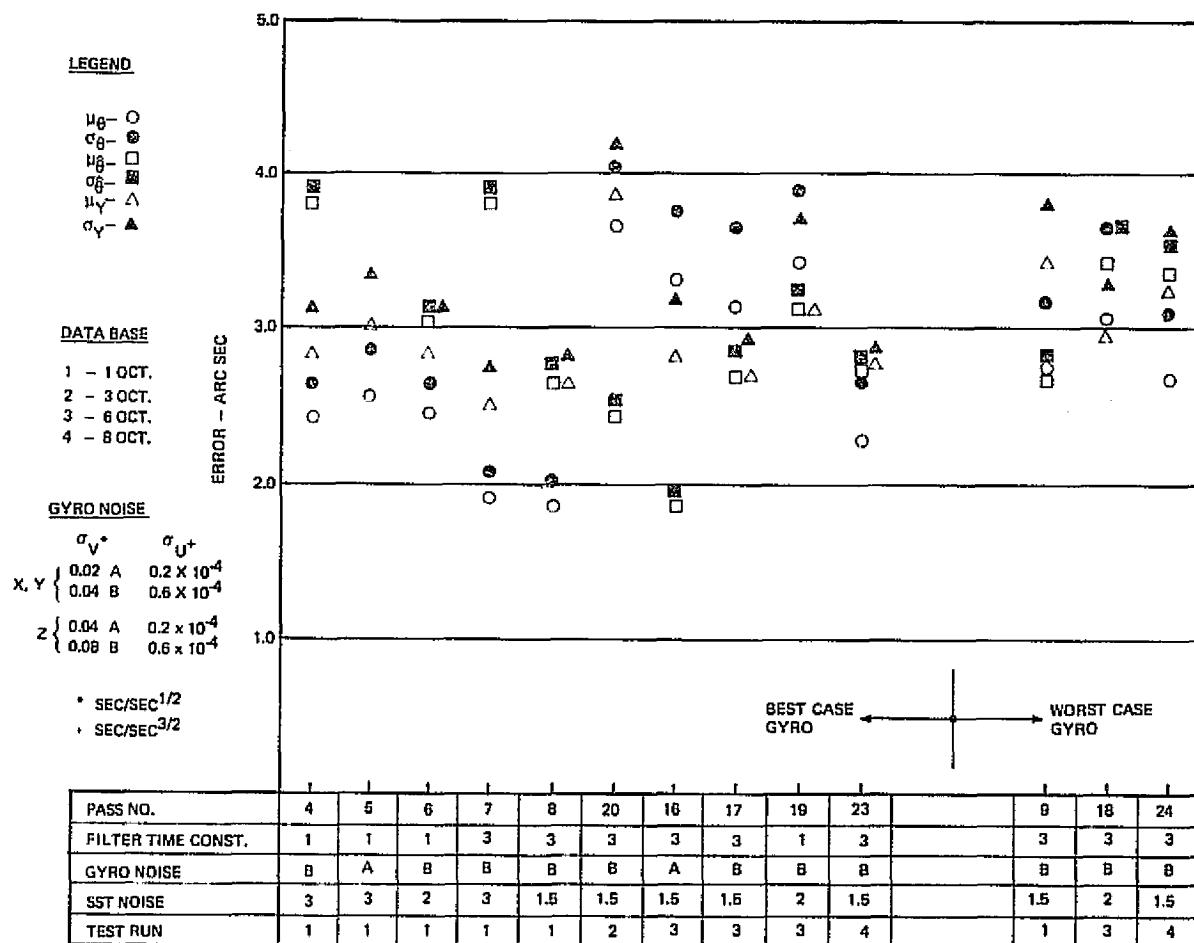


Figure 9-5. PADS Test Results - 20 Minute Updates

Additional examples of steady state performance are shown in Figure 9-6 to 9-10.

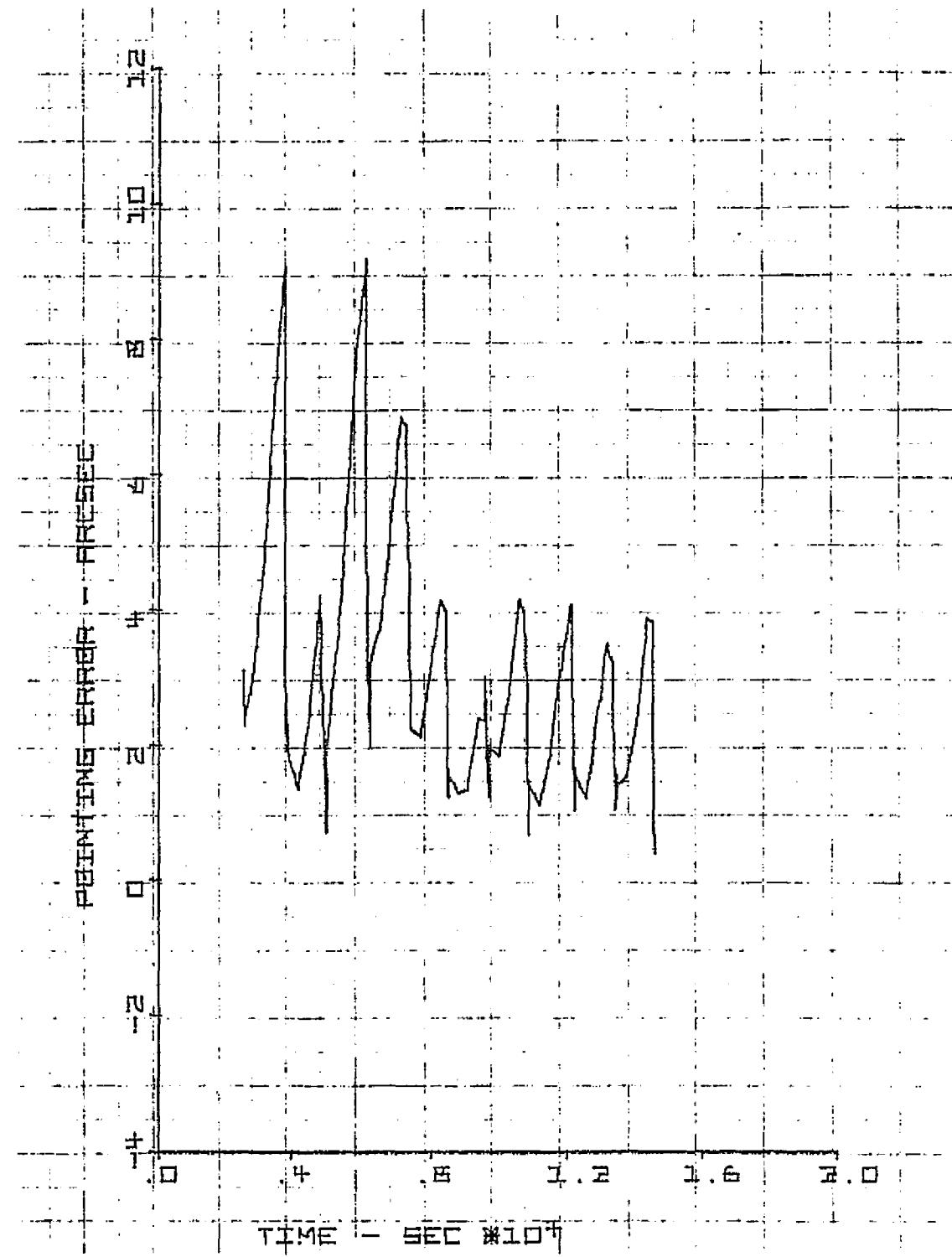


Figure 9-6. Pass No. 17

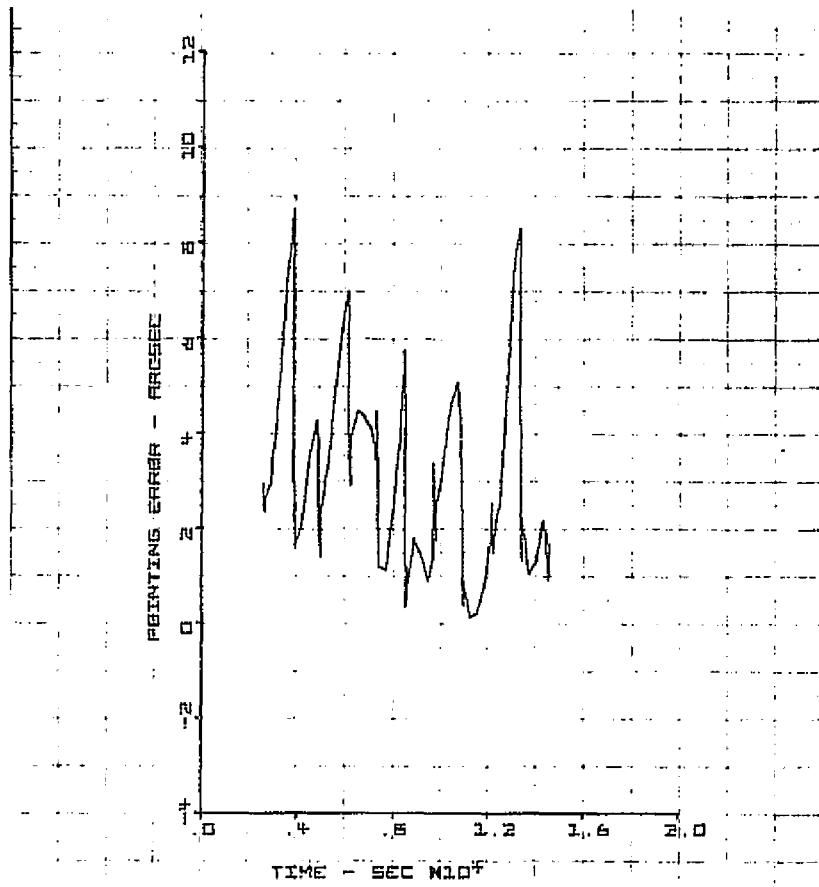


Figure 9-7. Pass No. 18

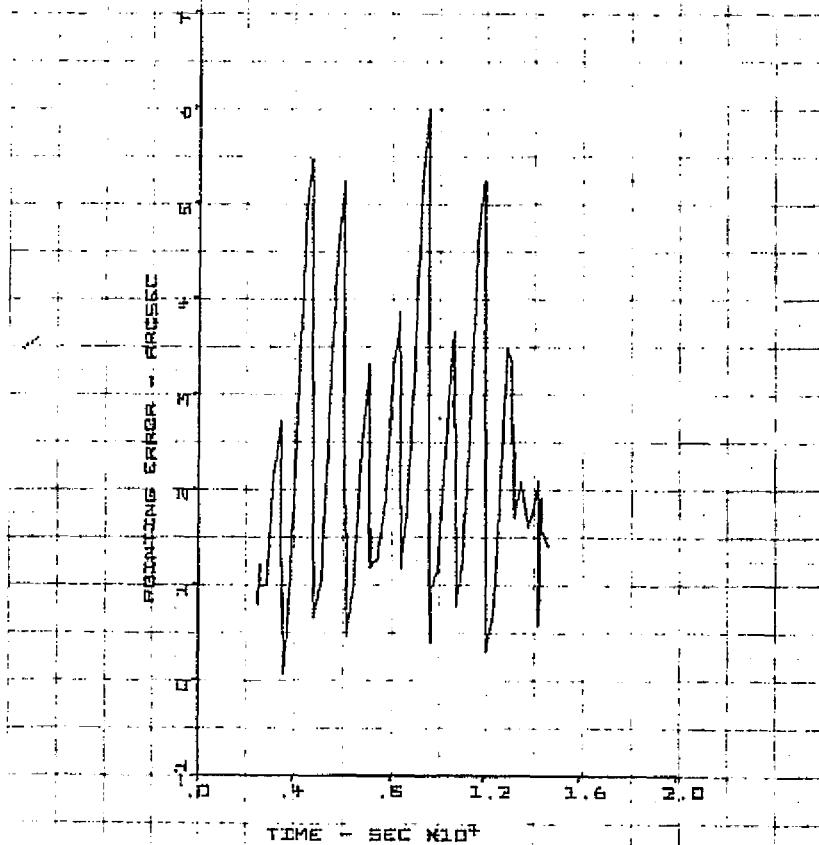


Figure 9-8. Pass No. 28

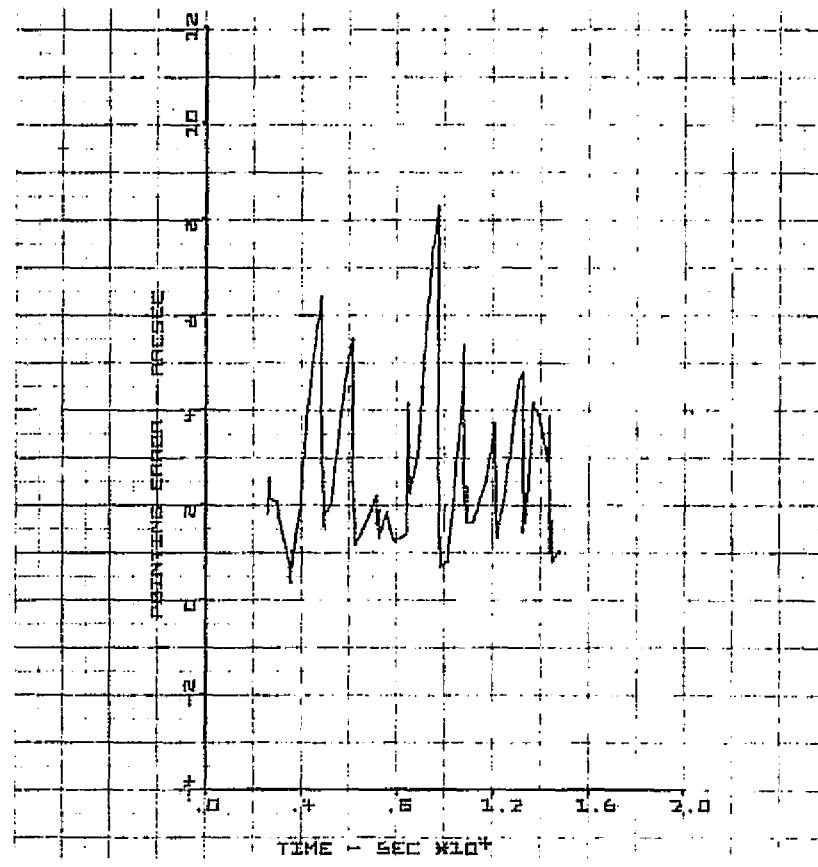


Figure 9-9. Pass No. 24

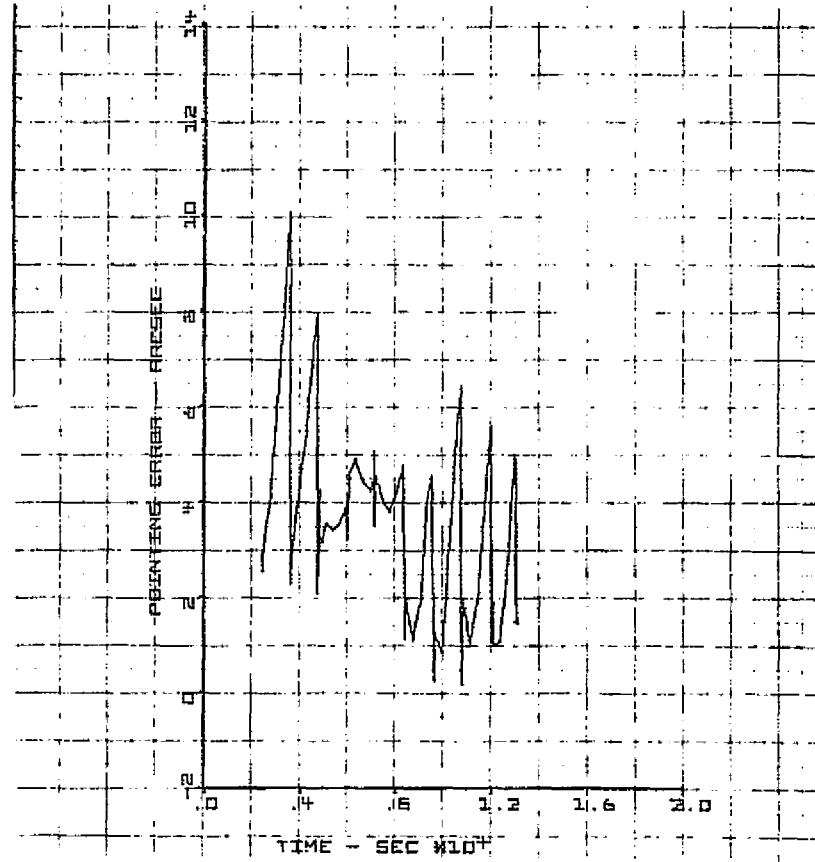


Figure 9-10. Pass No. 28

Figure 9-11 presents results similar to Figure 9-5, but for systems with less frequent star updates. In each case rapid initial convergence was obtained as the first two star updates were taken 20 min apart. Thereafter, the update interval was as noted, either 40 or 60 minutes. As anticipated, these results are somewhat poorer. Specifically:

- The peak 40 min RMS error, σ_θ , is 7 sec, with the average σ_θ given by 4.32 sec, or 3.06 sec, per axis.
- The peak 60 min RMS error, σ_θ is 13 sec, with the average σ_θ given by 7.72 sec, or 5.46 sec, per axis.
- The influence of worst case over best case gyro alignment is now much more severe, as much longer time intervals exist between gyro bias corrections.
- Test runs 1 and 4 indicate much better results than either 2 or 3. Test run 2 is particularly poor due to the aforementioned tracker bias.
- Passes 11, 13, 25, 26, 14, and 15 show fairly good agreement between actual and filter predicted performance.
- Passes 10, 30, and 31 show quite a difference between actual and predicted results. The latter two are influenced by the unobservable tracker bias, whereas Pass 10 uses gyro noise parameters which are pessimistic for these longer filtering durations. In practice, when the update intervals vary, the gyro noise parameters must assume some compromise values.

Figures 9-12 to 9-15 illustrate typical steady state behavior patterns for these increased update duration runs.

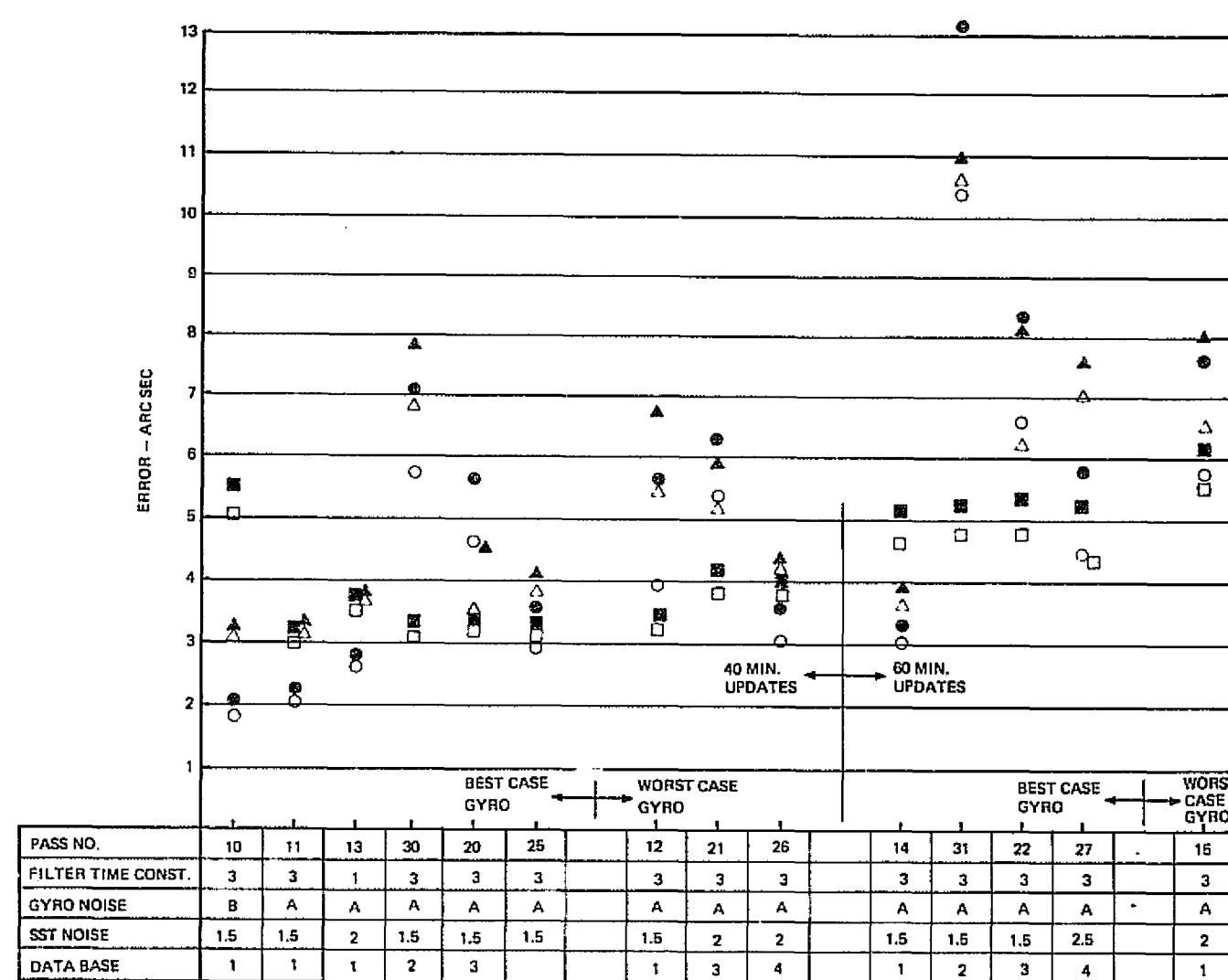


Figure 9-11. PADS Test Results - 40 and 60 Minute Updates.

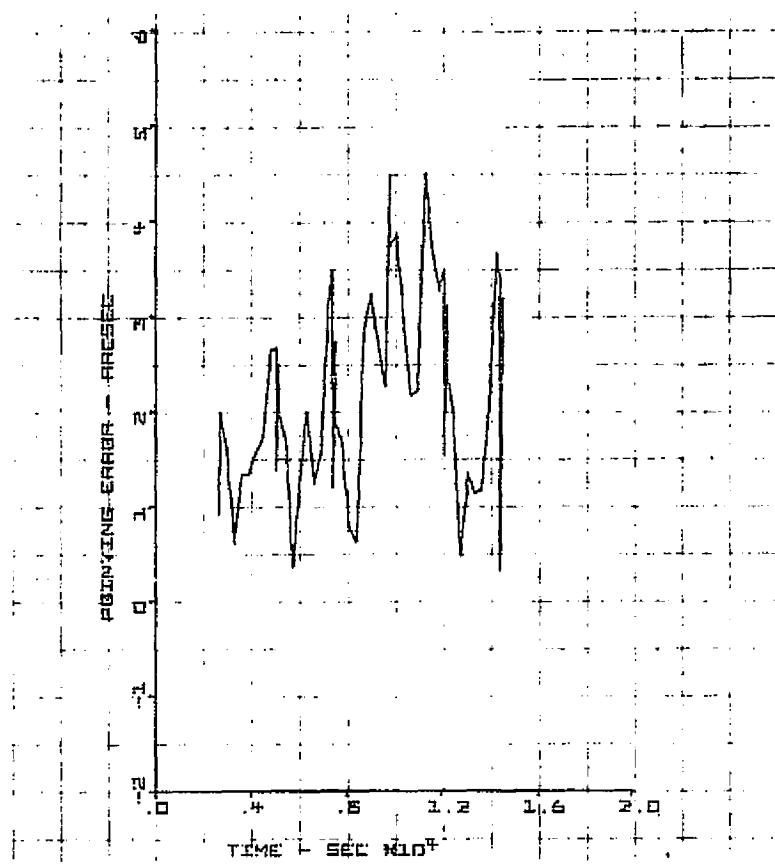


Figure 9-12. Pass No. 11

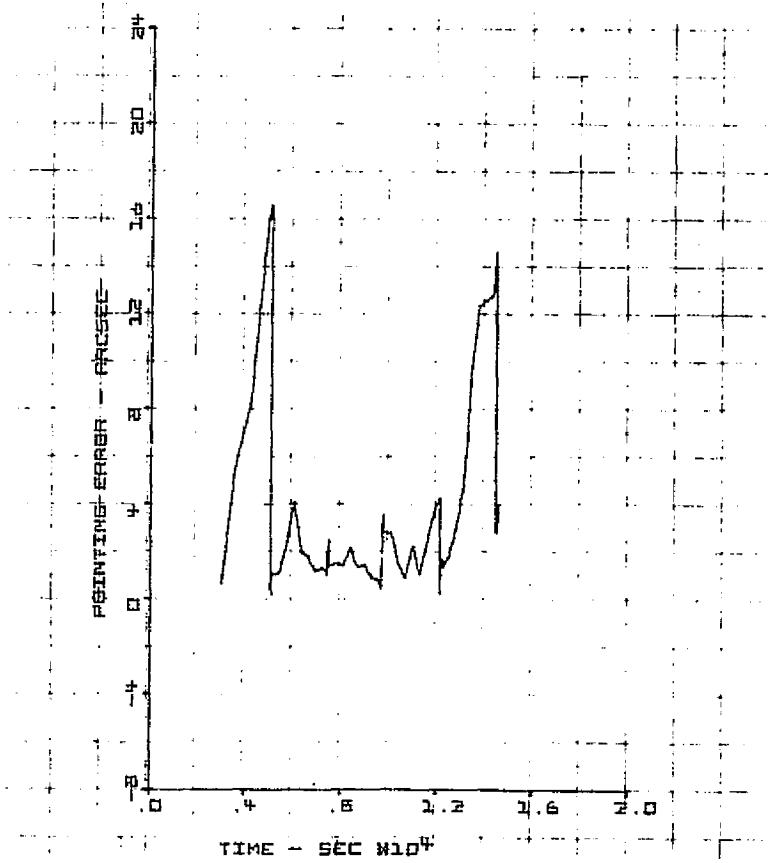


Figure 9-13. Pass No. 12

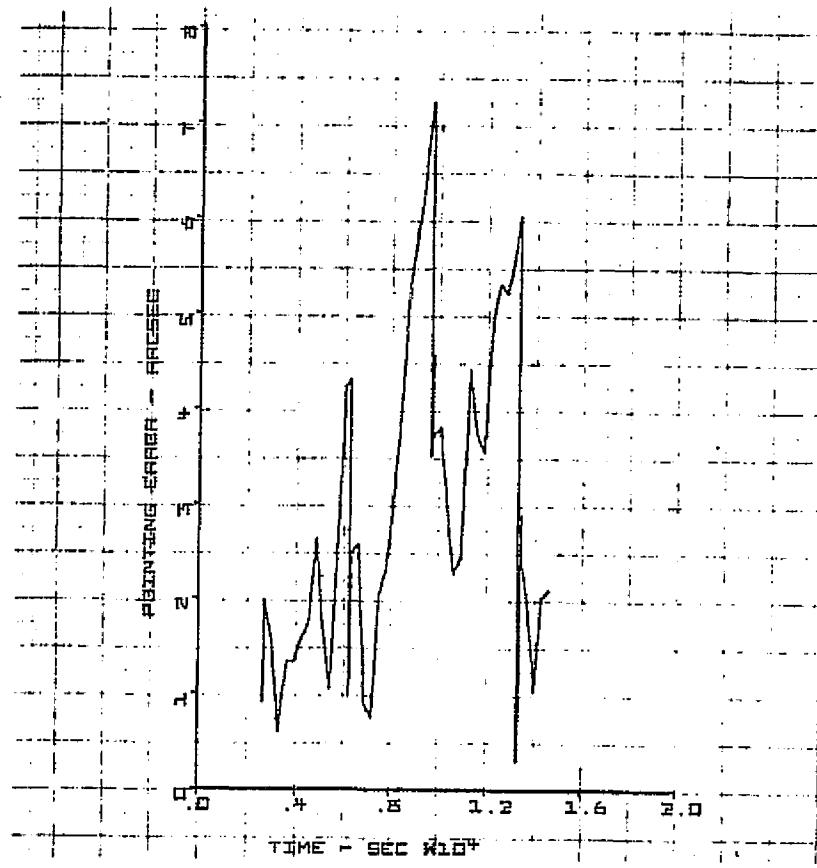


Figure 9-14. Pass No. 14

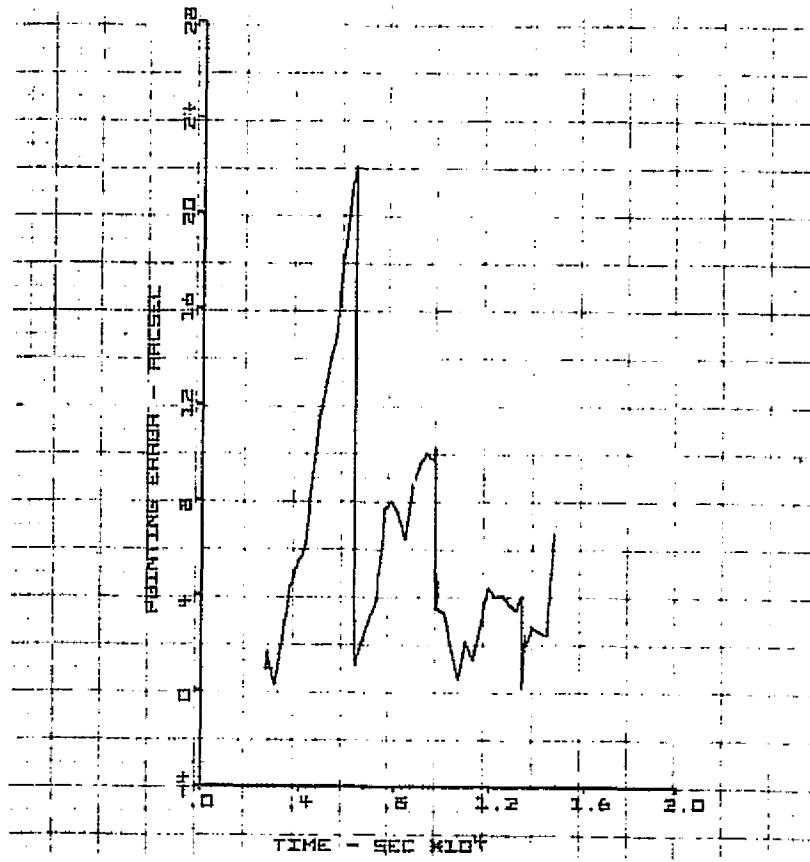


Figure 9-15. Pass No. 15

9.3.5 PADS Accuracy

The criteria for the accuracy of the PADS is the RMS of the difference between the PADS estimate of the inertial attitude of its reference axes and the true attitude of these axes as indicated by:

- 1) Laboratory instrumentation
- 2) A priori knowledge of earth rate and the inertial attitude of the laboratory at the start of a test run.

This criteria is designated σ_θ in Figures 9-5 and 9-11.

The parameters selected for the nominal PADS algorithm for the 20 minute updates are:

- 1) Filter time constant: 3 sec
- 2) Gyro noise (x and y gyros): $\sigma_v = 0.04 \text{ arc sec/sec}^{1/2}$
 $\sigma_u = 0.6 \times 10^{-4} \text{ arc sec/sec}^{3/2}$
- 3) SST noise: 1.5 arc sec.

The parameters for the 40 and 60 minute updates were the same except for the gyro noise sigmas which were reduced by 1/2 and 1/3 for σ_v and σ_u , respectively. The passes representative of the values in Figure 9-5 are numbers 8, 28, 17, and 23, or test runs 1, 2, 3, and 4, respectively. In Figure 9-11 the 40 minute update representative passes are numbers 11, 30, 20, and 25, or test runs 1, 2, 3, and 4, respectively. The 60 minute update representative passes are numbers 14, 31, 22, and 27, or test runs 1, 2, 3, and 4, respectively.

Table 9-2 summarizes the value of σ_θ for the nominal PADS algorithm with the best gyro orientation. Values from all four test runs are available for each update interval. The rms of the values for the four runs is the PADS two-axis error for a given update interval. This rms, divided by $\sqrt{2}$, is the PADS single-axis error.

The PADS design goal is 3.6 arc seconds (1σ) per axis for 20 minute star updates. The measured error of 2.3 arc seconds is well within the design goal.

Table 9-2. PADS RMS Error

Test Run	20 Minute Updates	40 Minute Updates	60 Minute Updates
1	2.0	2.3	3.3
2	4.0	7.1	13.5
3	3.7	5.7	8.3
4	2.7	3.6	5.8
rms (2-axis)	3.2	5.0	8.6
rms (1-axis)	2.3 arc sec	3.6 arc sec	6.1 arc sec

The increase in measured error with increased update interval is also indicated in Table 9-2. Although the increase appears well behaved, examination of the individual test runs reveals a large variation in values, indicating caution should be applied in generalizing these results.

10. GIMBAL SYSTEM TEST

This section describes the gimbal system test which was run from 6 February 1976 to 16 February 1976. The orbit scenario on which the test was based is described along with comments regarding initial alignment of the PADS axes. All of the four test runs which were conducted during the ten day test period are analyzed using several performance measures. Two of the test runs were selected for detailed analysis to illustrate the effect of individual error sources on the PADS attitude estimates. A parametric analysis is made to evaluate the effect of star update interval on the PADS accuracy. Lastly, a summary of the PADS accuracy is presented.

10.1 TEST DESCRIPTION

The spacecraft configuration postulated for the PADS system test is that of a three-axis stabilized, earth-pointed satellite in geosynchronous orbit. An experiment on board, a telescope, for example, requires precise information regarding the inertial attitude of its sensitive axis or axes. The PADS is used to provide this information.

A calibration of the PADS gimbal star tracker axes relative to the experiment axes is allowed once every ten days. Following a calibration the experiment may require the PADS attitude information for any length of time, for any number of times, during the next ten days.

By way of configuring a practical laboratory test, four test runs, nearly evenly spaced in time, were conducted during a ten day test period. The first three runs were four hours in duration, the last was five hours. During each run a star update was made every 20 minutes. This corresponded to a star being available every 5° in right ascension. Three different star declinations over approximately a 40° span were used. All stars were $3.5 M_V$ GO (6000^0K).

The test period was limited to ten days by the scope of the PADS contract and not by an assumed limitation in the stability of the star tracker. Four runs during the ten day period were adequate to measure the day-to-day stability of the tracker. Four hour runs were sufficient to ensure steady-state behavior for star updates up to 40 minutes apart. The five hour run was made to provide data for star updates 60 minutes apart. The minimum

star update time of 20 minutes was determined by the gyro performance (see Section 4.1). The maximum star separation in declination of 40° was considered adequate to provide three-axis information with the single star tracker. Making all stars $3.5 M_V$ presented a worst case situation in terms of tracker noise and simplified test equipment design.

10.2 INITIAL ALIGNMENT

Alignment of the gimbal star tracker presented considerably more complexity than that encountered with the strapdown star tracker. In the case of either tracker the objective was to determine the alignment of the electro-optical (EO) axes relative to optical surfaces on the tracker base. For the strapdown tracker the only critical EO axis was the EO boresight, i.e., that position in the field of view at which a star produced zero electronic output in two axes. Using the parallel beam star stimulus approach, it was an easy task to align the boresight normal to the front face of the optical cube within an arc second. However, the gimbal tracker has two EO axis which are critical: 1) the EO boresight zero position, defined as that position of a star wherein both optical sensor field of view outputs are zero, and the gimbal angle readout is also zero, and 2) the normal to that plane for which the angle of incidence between the plane and the EO boresight remains constant for all gimbal angles. The second axis is the effective gimbal axis, purposely defined in an electro-optical rather than a mechanical sense. The obliqueness of the definition is necessary to account for a possible nonorthogonality between the EO boresight and the effective gimbal axis. Determining the orientation of both these EO axes relative to the three mirrors attached to the base of the tracker to within one arc second entailed a significant activity.

The first step undertaken was identification of the effective gimbal axis. Ideally this should have been accomplished electro-optically, but no practical technique was available to do this with an arc second accuracy. Consequently, recourse was made to an optical-mechanical technique. This consisted of mounting a mirror on the end of the gimbal axis with its surface normal to the gimbal axis. Normality was observed by autocollimating off the mirror with a theodolite and adjusting the mirror orientation until no deflection was observed with the theodolite as the gimbal was attached

mirror were rotated. Performance of this task led to two observations: 1) the gimbal axis sagged such that the mirror on the end of the axis tilted 34 arc seconds from the effective gimbal axis, and 2) the rate of change of this sag was 4 arc seconds for a gimbal motion of 30° . Both of these effects are shown in Figure 10-1. The sag was determined by leveling the gimbal axis using the optical cube on the optical sensor. With the theodolite viewing the back face (negative boresight axis) of the cube, the tracker base fixture was shimmed until no horizontal deflection was measured as the gimbal was turned through 20° . In view of the method used, the accuracy of the measured sag is probably no better than 5 arc seconds. On the other hand, the relative change of the sag with gimbal angle was measured directly with the theodolite, and its accuracy is better than one arc second.

The gimbal axis sag theoretically should have no significant effect on the performance of the star tracker. However, it did invalidate accurate determination of the vertical alignment of the effective gimbal axis through optical-mechanical techniques. In view of the symmetry of the curve in Figure 10-1 about the ordinate, and the mechanical symmetry of the plus and minus 30° gimbal positions relative to the gravity vector, it was assumed that the horizontal component of the mirror normal was within an arc second of the effective gimbal axis.

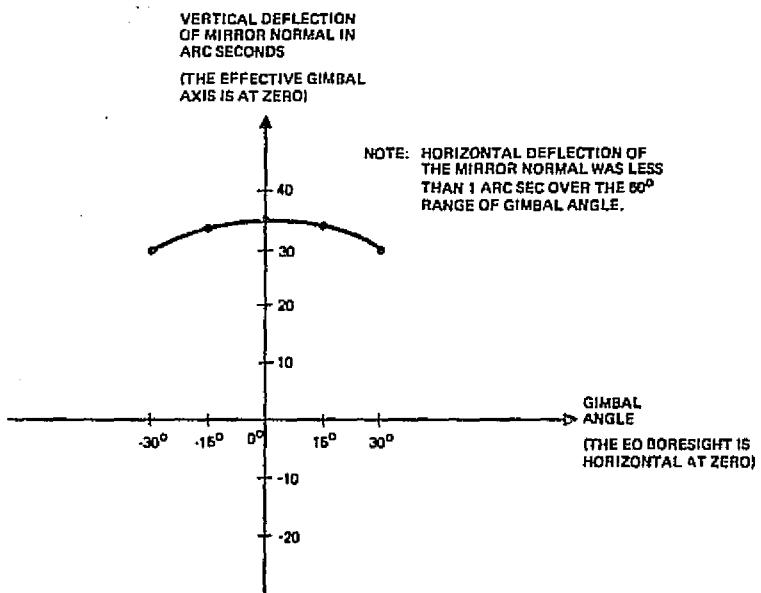


Figure 10-1. Gimbal Axis Sag

The next step in the alignment procedure was to adjust the EO boresight normal to the effective gimbal axis. This was accomplished using two theodolites as shown in Figure 10-2. The tracker base was turned until the sum of the two angles indicated in the figure was 90° . The optical sensor was then rotated in the gimbal until zero horizontal output was obtained. Using both theodolites in this manner gave an accuracy of one or two arc seconds for this step.

With the EO boresight now aligned normal to the effective gimbal axis, the relative orientations of the three reference mirrors were determined through the use of the parallel beam star stimulus technique. With the tracker in place the stars were adjusted via the rotating mirror assembly so that the three star beams were normal to the three tracker reference mirrors. Immediately following this the star tracker was removed and the theodolite inserted in its place. The theodolite was then used to measure the relative orientations of the star beams. The results were previously shown in Figure 4-21 and are repeated in Table 10-1.

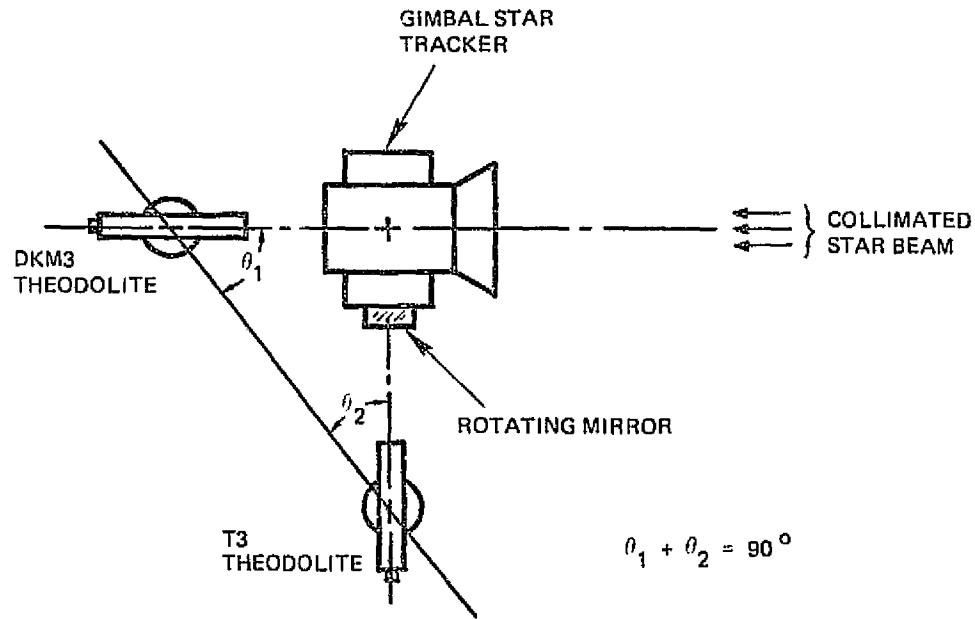


Figure 10-2. Alignment of the EO Boresight to the Effective Gimbal Axis

Table 10-1. Relative Reference Mirror Orientations

Mirror No.	Vertical (arc sec)	Horizontal (arc sec)
1	+68380.2	-3.2
2	0.0	0.0
3	-68392.8	-4.8

The last alignment step was to determine the orientation of the three mirror normals relative to the tracker axes. Immediately prior to the system test, with the tracker in place, the orientation of the tracker axes relative to the stars was measured using the tracker outputs, and the orientation of the stars relative to the mirror normals was measured using the parallel beam technique and the automatic autocollimator outputs. Combining the two sets of measurements gave the results shown in Table 10-2. The numbers in parenthesis are the relative orientations.

Table 10-2. Reference Mirror Positions in Tracker Axes

Mirror No.	Vertical (arc sec)	Horizontal (arc sec)
1	53814.9 (68379.9)	-9.6 (-5.2)
2	-14564.8 (0.0)	-4.4 (0.0)
3	-82958.0 (-68393.2)	-8.2 (-3.9)

Comparison between Tables 10-1 and 10-2 leads to two observations. First, if the coordinates in Table 10-1 are rotated 4.5 degrees as shown in Figure 10-3, then the agreement between the relative horizontal measurements from the two tables is within 0.5 arc second. This indicates that: 1) the boresight axis was accurately aligned normal to the effective gimbal axis, and 2) the angles between the mirror normals and plane orthogonal to the gimbal axis are accurately known. Secondly, the agreement between the relative vertical measurements indicates that the gimbal readout, at least for the three positions measured, does not have to be calibrated.

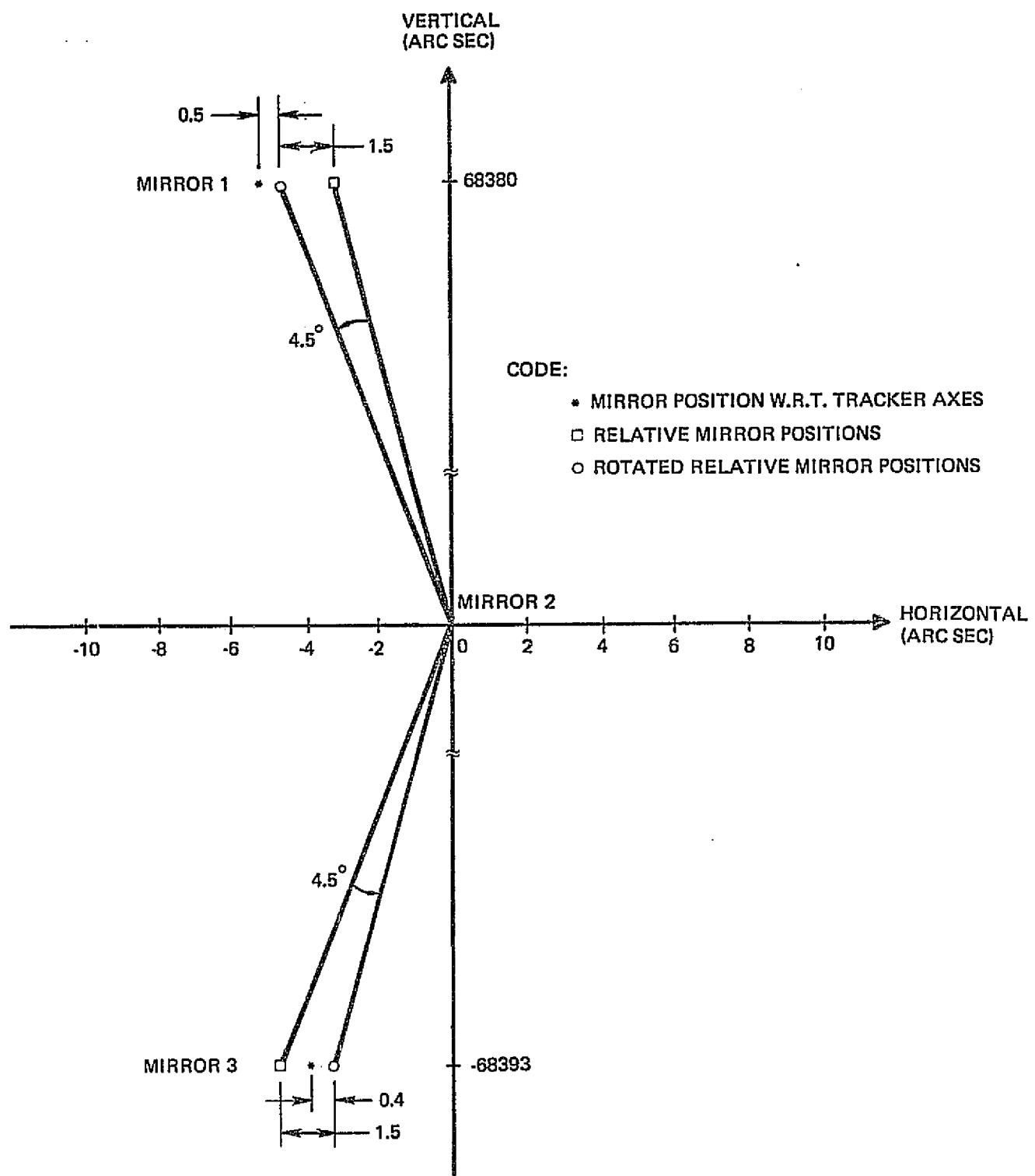


Figure 10-3. Relative Locations of Mirror Normals

10.3 SYSTEM TEST RESULTS

The following system test results were obtained using the computer performance evaluation programs described in Section 8.

10.3.1 Pass Parameters

Four test runs, each of approximately four hours in duration, were conducted between 6 February 1976 and 16 February 1976. The time-tagged sensor data was then utilized by the Estimation Algorithm to predict both laboratory attitude and the gyro drift rates. As before, the algorithm requires a number of additional inputs dealing primarily with statistical quantities that describe initial uncertainties in both attitude and gyro drift rates, as well as uncertainties in both gyro and GST noise parameters. These parameters are listed in Table 10-3. Varying these parameters, a total of 31 attitude estimations passes were made based upon the four test runs mentioned above.

10.3.2 Performance Measures

The effectiveness of the Attitude Estimator as a three axis device is based primarily upon three things:

- 1) The degree to which the estimator accurately predicts the attitude of the laboratory. If θ_1 , θ_2 , and θ_3 represent the estimation errors about, respectively, the x_1 , x_2 , and x_3 axes, then the attitude error is defined by

$$\theta = \sqrt{\theta_1^2 + \theta_2^2 + \theta_3^2} \quad (10-1)$$

- 2) The degree to which the laboratory attitude error, which of course is unknown operationally, is reflected by the estimator's error covariance prediction. Observation of the latter should give a strong indication of the actual errors. In practice, the operator will compare the attitude error covariance prediction with the GST measurement residuals in order to check estimator "consistency."
- 3) The speed with which the attitude estimates converge from sizeable initial estimation errors (e.g., 100 sec), to errors that are close to "steady state."

Items 1) and 2) are time variant and require additional quantification if clear figures of merit are to be adopted. In this regard, the per axis mean pointing error and its standard deviation are computed as described in Section 9.3.2.

Table 10-3. Conditions and Parameters of Computer Passes

Pass Conditions

Run Duration - 14500 to 18370 sec

Star Update Interval - 20 min/40 min/60 min*

Each star utilized once near the azimuth center of the GST field of view

Initial Conditions

Initial Attitude Estimate - 100 sec error about x_1 , x_2 , and x_3

Initial Attitude Uncertainty (1σ) 100 sec about x_1 , x_2 , and x_3

Initial gyro drift rate uncertainty - 0.02 sec/sec

Sensor Parameters

Gyros:

Estimated Drift rates. Gyro x -0.840 sec/sec

y -0.422 sec/sec

z -1.165 sec/sec

Gyro noise v - 0.02 to 0.08 sec/(sec) $^{1/2}$ *

Gyro noise u - 0.2×10^{-4} to 0.6×10^{-4} sec/(sec) $^{3/2}$ *

Gyro noise e - 0.1 sec

Gimbal Tracker:

Time constant (both axes) - 0.0466 sec

Digital Output filter (both axes) - 3 sec

Output noise (both axes) - 1.5 sec

* Specified in Test Run

10.3.3 Detailed Analyses of Passes No. 11 and No. 21

Pass No. 11 corresponds to the general conditions of Table 10-3 and utilizes the PADS data of 9 February, the gyro being updated every 20 minutes by the gimbaled star tracker. Figures 10-4 and 10-5 show, respectively, the corresponding two and three axis convergence of the laboratory attitude estimation errors. A total of 12 star updates are employed, in the order

$$\text{Star Number: } 1,3,3,3,1,3,2,1,3,1,2,3,3 \quad (\text{A})$$

where, noting Figure 8-4, the tracker input star line-of-sight has a large negative projection on x_3 for star No. 1, a slight positive projection for star No. 2, and a large positive projection for star No. 3. The particular sequence noted above was chosen to insure the differing geometric conditions inherent in sighting different stars for the more demanding convergence conditions associated with 40 and 60 minute updates. Thus when 40 minute update passes are made, the star sequence is

$$\text{Star Number: } 1,3,1,2,3,2,3 \quad (\text{B})$$

and for 60 minute updates passes

$$\text{Star Number: } 1,3,2,1,3 \quad (\text{C})$$

The sequence (A) is not optimally beneficial in assuring rapid convergence for 20 minute update passes, as star No. 3 is used 3 successive times. This is the price paid for better results when the updates are less frequent.

For Pass No. 11, the first five updates occur at times 329, 1365, 2649, 3850, and 5044 sec, corresponding to stars 1,3,3,3,1 respectively. As the results of Figures 10-4 and 10-5 indicate, the first two updates (providing 4 pieces of independent azimuth-elevation star data) considerably reduce the initial error, but are not adequate to establish the six unknowns defined by the three attitude and three gyro drift rates. Additional updates by star No. 3 at 2649 and 3850 sec provide only slight improvement as the geometric conditions are not much different than at 1365 sec. Once star No. 1 is again used (at 5044 sec) a dramatic improvement occurs, and the filter can subsequently be considered to be close to its "steady state" operation. The reuse of star No. 1 proved geometrically beneficial as its previous use occurred sufficiently far in the past. This same convergence pattern appeared in all of the 20 minute update passes, regardless of which PADS test run was used.

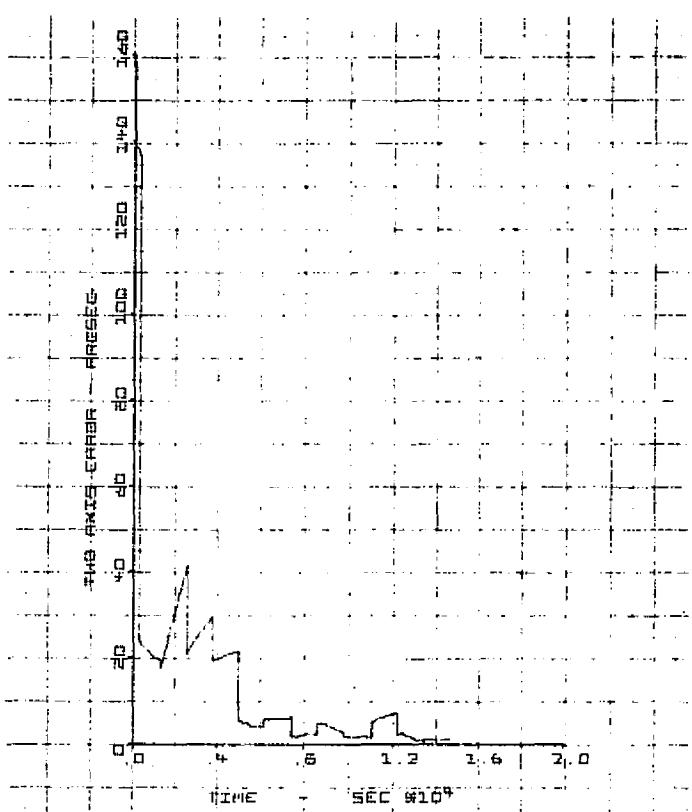


Figure 10-4. Pass No. 11 - Two Axis

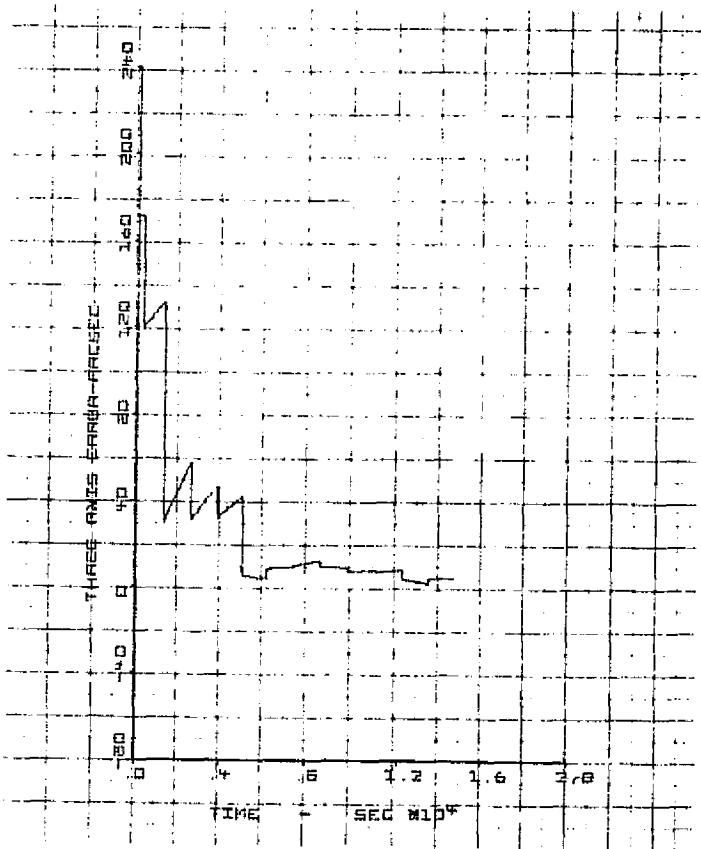


Figure 10-5. Pass No. 11 - Three Axis

Figure 10-6 shows a comparable three-axis run for the test data of 6 February. Convergence behavior is essentially the same as described above, but there appears a dramatic temporary degradation in the attitude estimates at about 8000 sec, long after the filter has supposedly reached "steady state." This is caused by a severe shift in the z gyro drift rate at about the same time, as indicated by the gyro data of Figure 10-7. Of significance is the fact that the filter is only temporarily confused by this event, providing better and better estimates of the new z gyro drift rates as additional star updates appear.

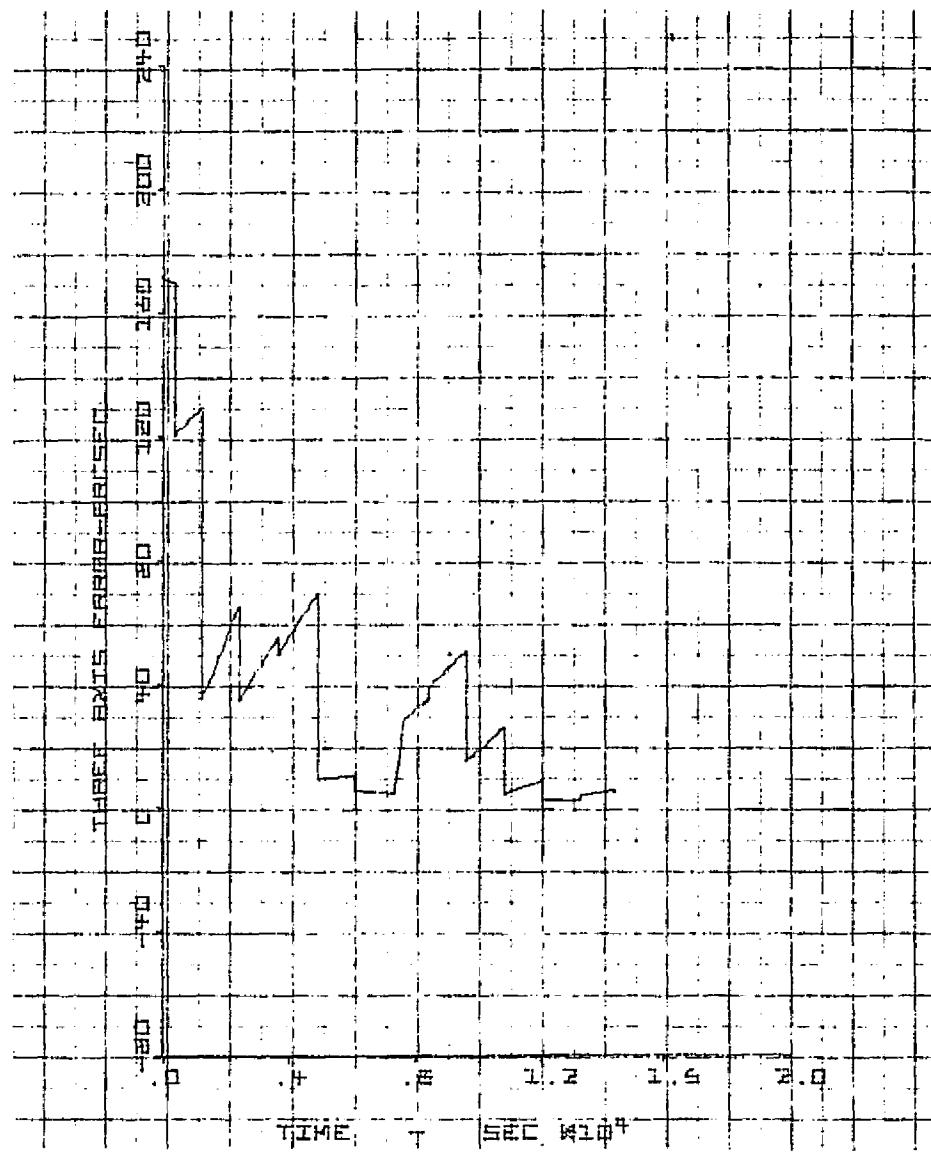


Figure 10-6. Pass No. 21 - Three Axis

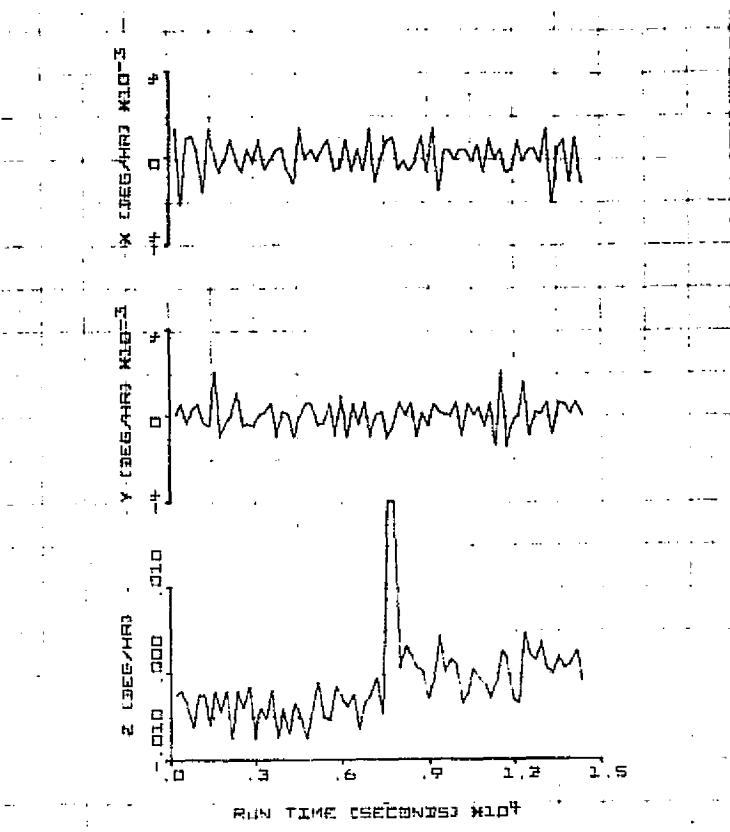


Figure 10-7. 02/06/76 Run (200 Sec/Sample)

10.3.4 PADS Steady State Parametric Test Results

The results for the runs taken on the 9th, 11th, and 16th of February are shown in Figure 10-8, for 20 minute updates. The statistics presented in each case cover the time interval subsequent to the fifth star update to the end of the run. The results of the PADS data taken on 6 February are not included as the severe jump in the z gyro drift rate provides untypically pessimistic answers. The following conclusions are evident from Figure 10-8.

- Passes 11 and 13 provide two-axis estimates between 3 and 4 sec² and show good agreement to both the corresponding filter estimates and the measurement residuals.
- Pass 12 indicates poorer results than either 11 or 13. This can be traced to anomalous drift rate behavior of both the x and y gyros as each gyro's drift rate suddenly shifts by 0.0014 deg/hr at one point in the run. The effect is not major, but has sufficient impact to negatively influence a short test run of only 4 hours.

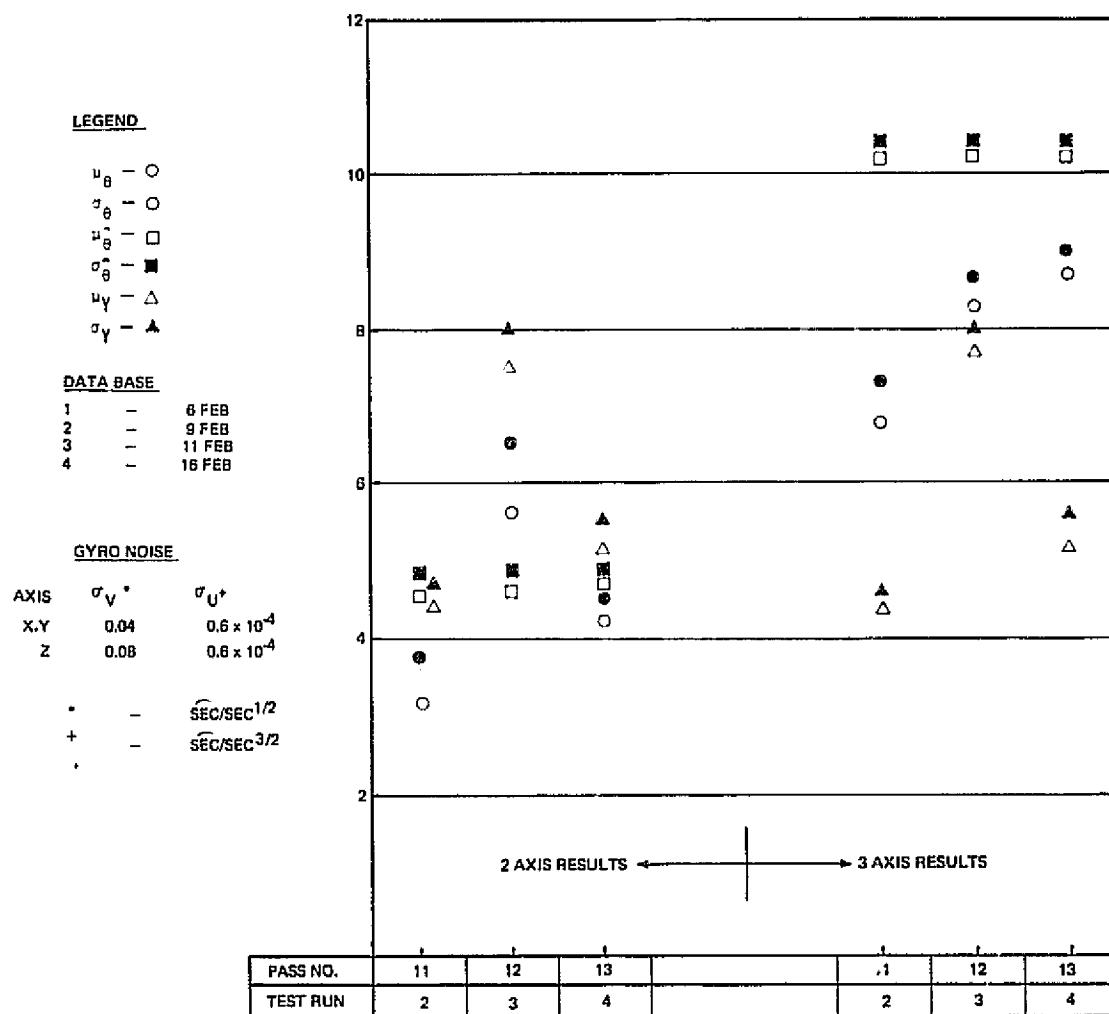


Figure 10-8 Gimbaled PADS Test Results (20 Minute Updates)

Figures 10-9 to 10-12 show typical convergence responses of the 20 minute update results.

Figure 10-13 shows results for 40 and 60 minute update intervals. Only test run 4 is shown for the latter, as this somewhat lengthened run alone allows an adequate number of updates necessary for "steady state" behavior. Even at that only the two axis results of Pass 18 have reached what can be considered final values. Errors about x_2 would have continued to reduce had the run time been longer.

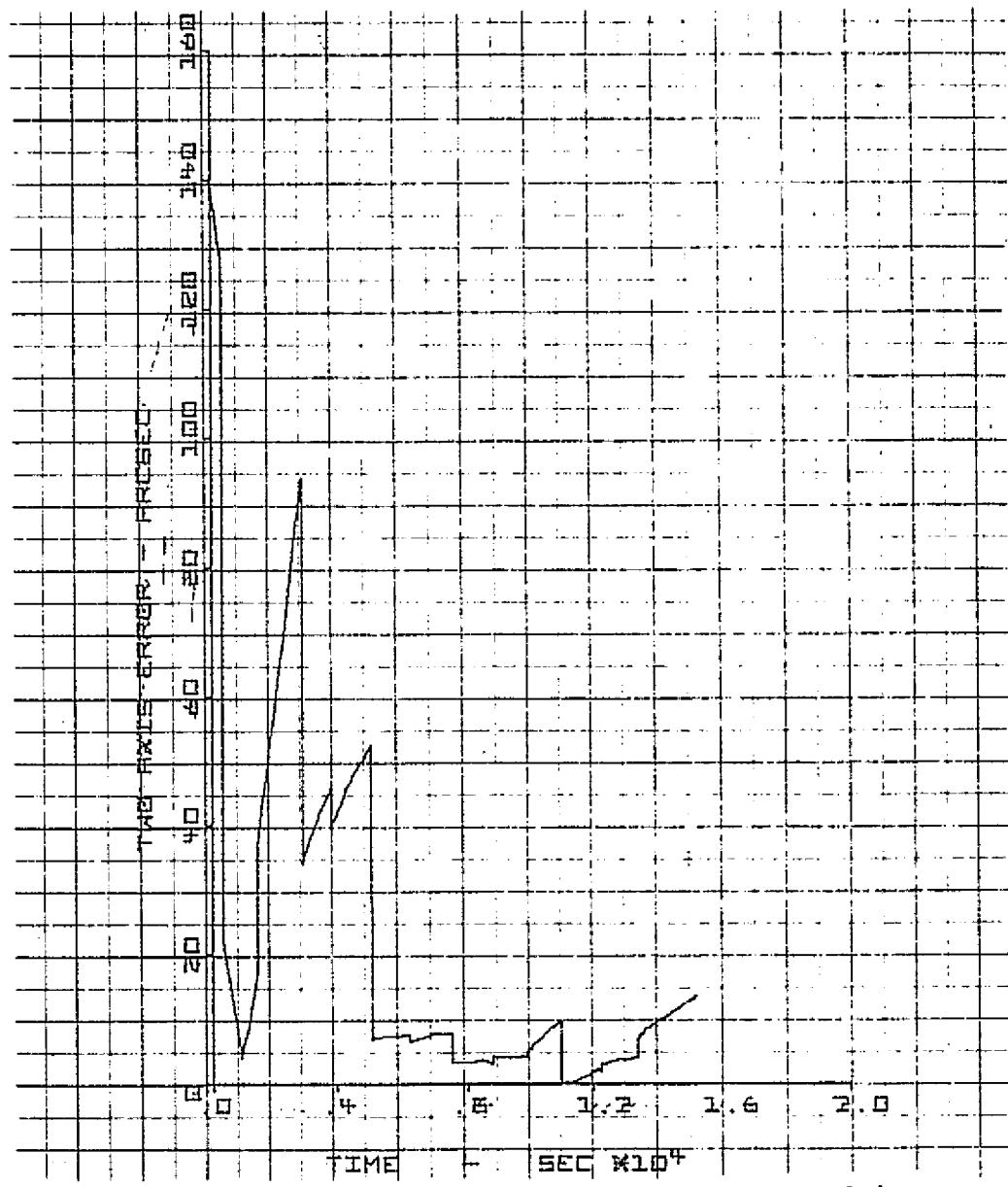


Figure 10-9, Pass No. 12 - Two Axis

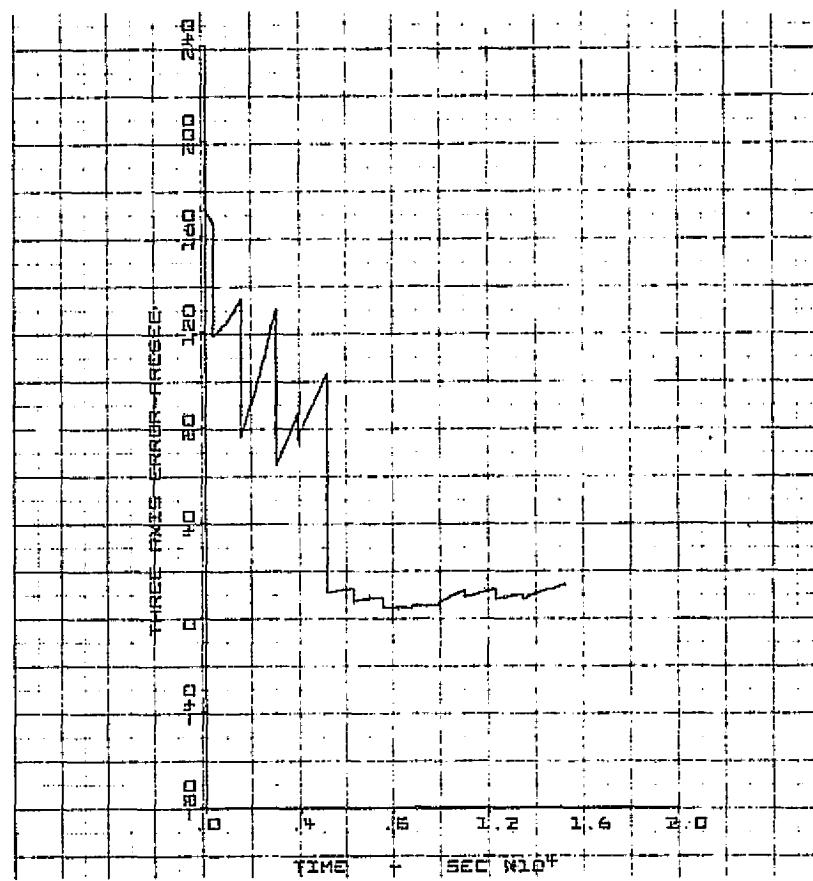


Figure 10-10. Pass No. 12 - Three Axis

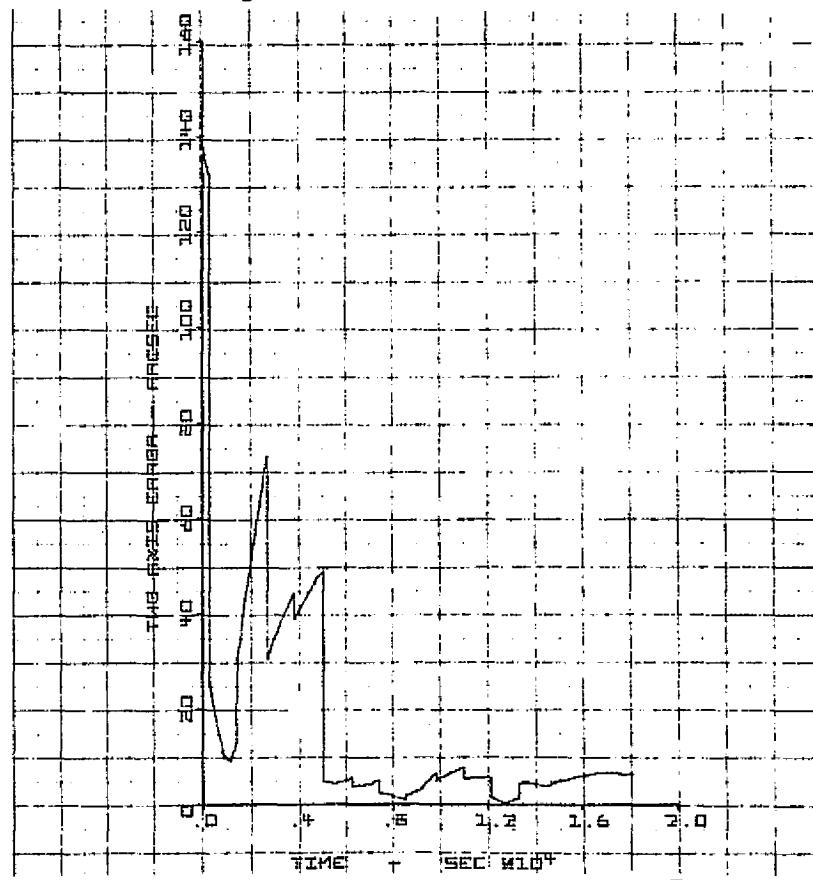


Figure 10-11. Pass No. 13 - Two Axis

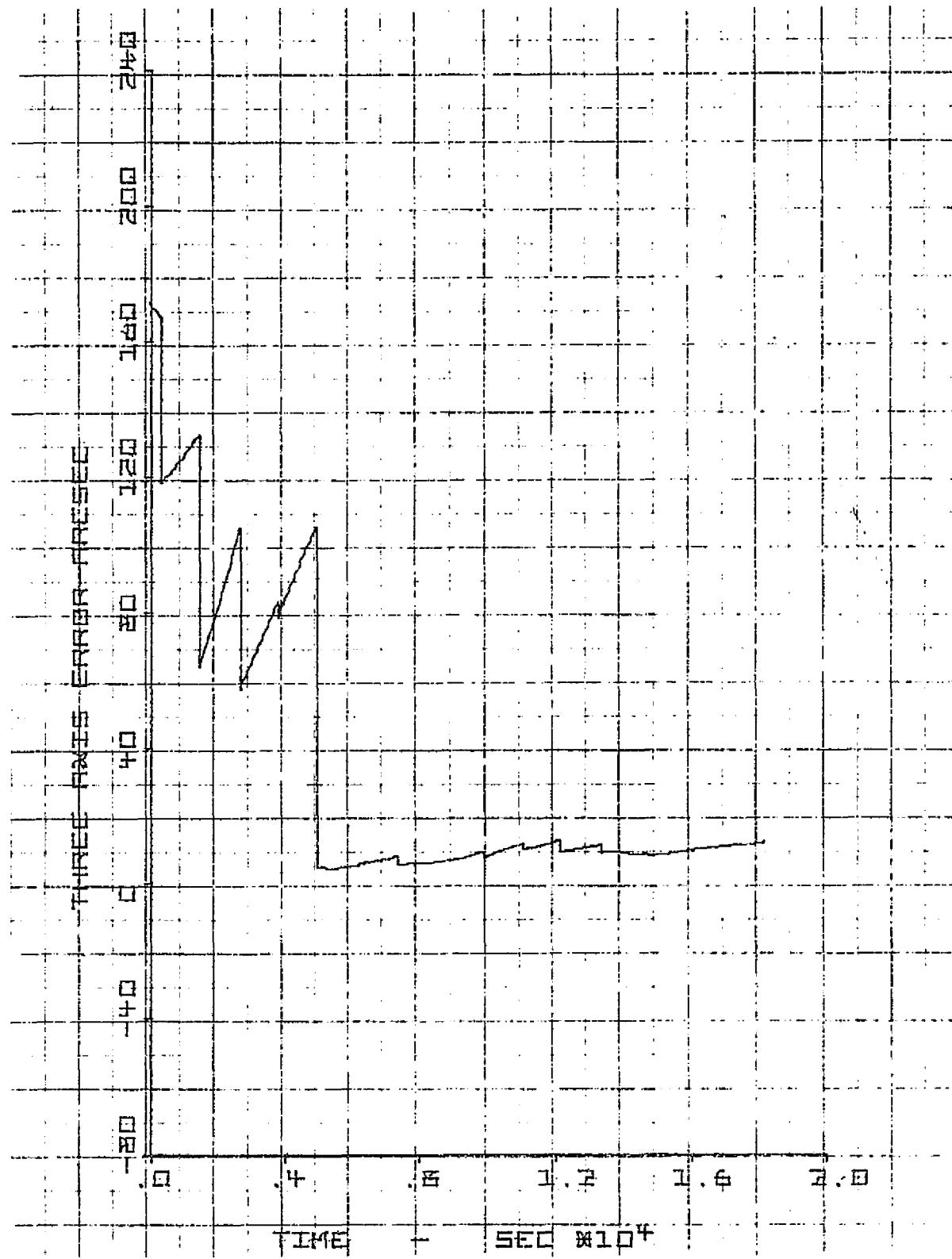


Figure 10-12. Pass No. 13 - Three Axis

10-16

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ORIGINAL PAGE IS POOR

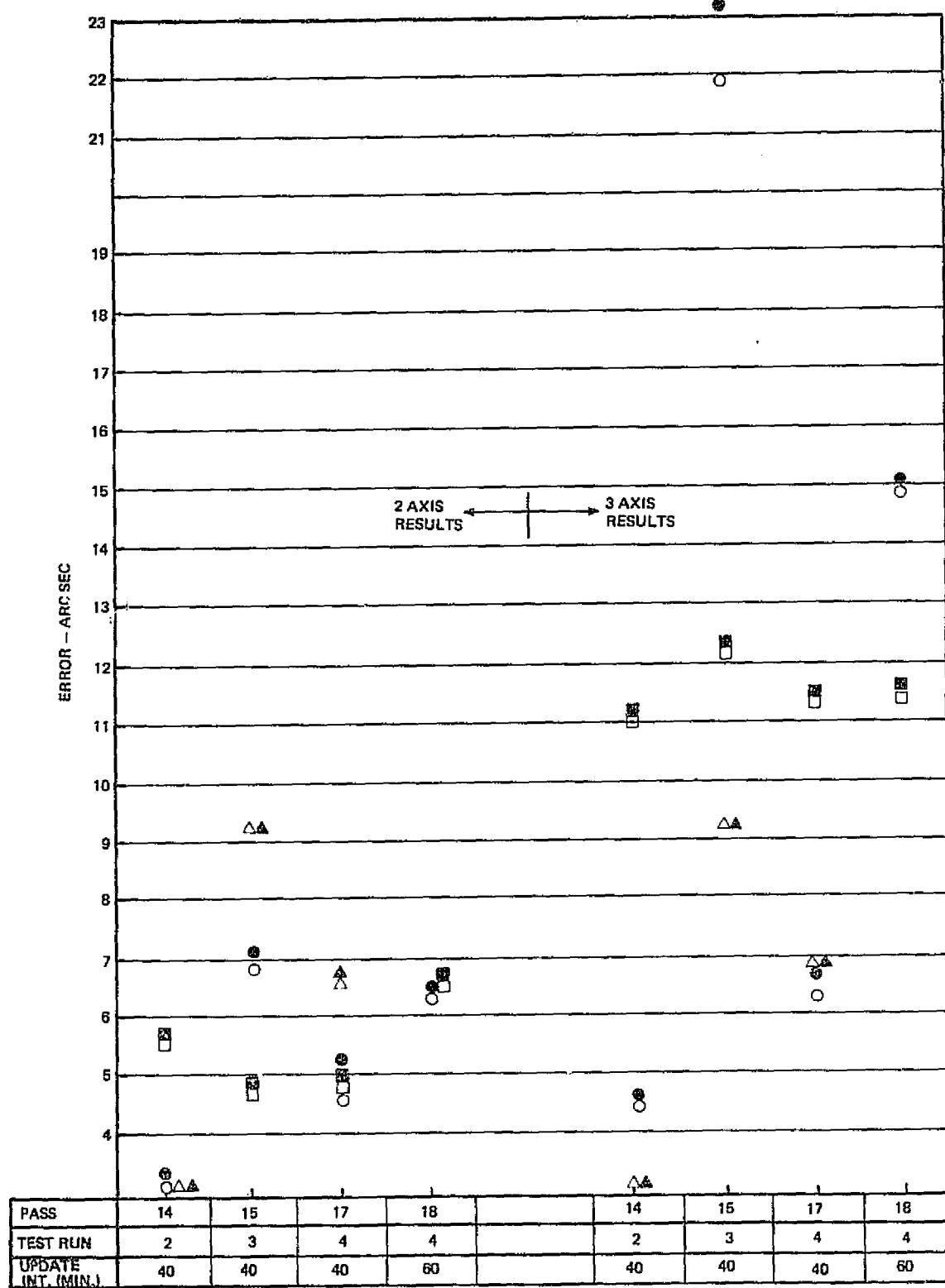


Figure 10-13. Gimbaled PADS Test Results -
40 and 60 Min. Updates

Of the 40 minute update passes, Passes 15 and 17 perform very well, although the three-axis filter confidence has clearly not settled to its final value as errors about x_1 inherently require more star data. The performance of Pass 15 is somewhat worse, again being plagued by the drift rate change of the x and y gyros noted before. Figures 10-14 to 10-17 illustrate these 40 and 60 minute updating runs.

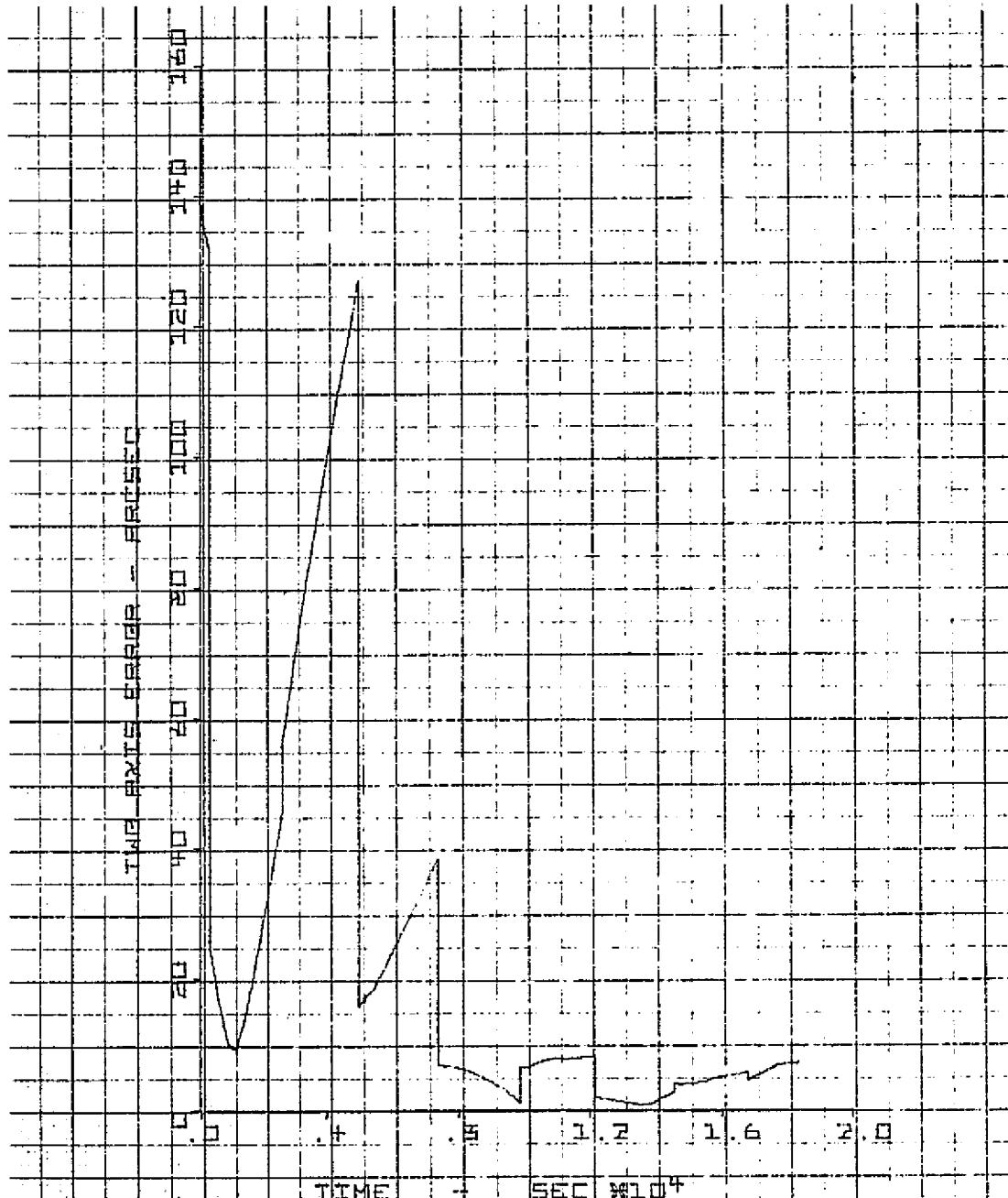


Figure 10-14. Pass No. 17 - Two Axis

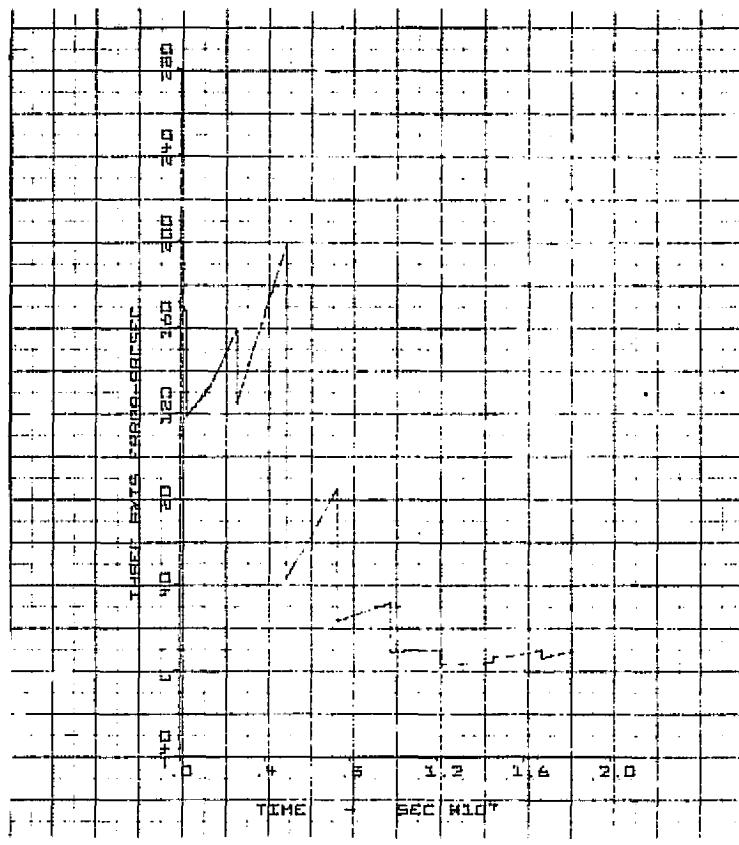


Figure 10-15. Pass No. 17 - Three Axis

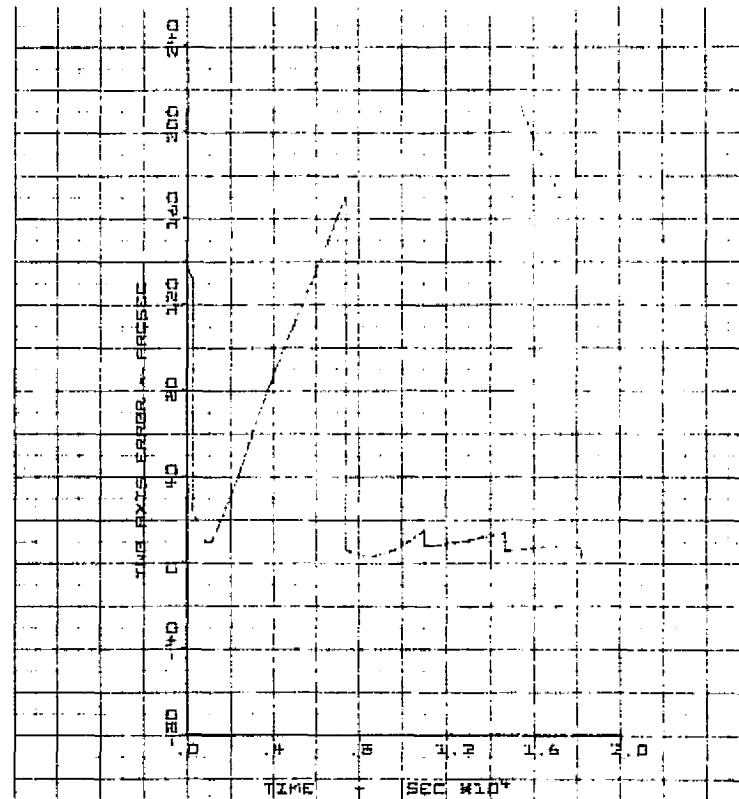


Figure 10-16. Pass No. 18 - Two Axis

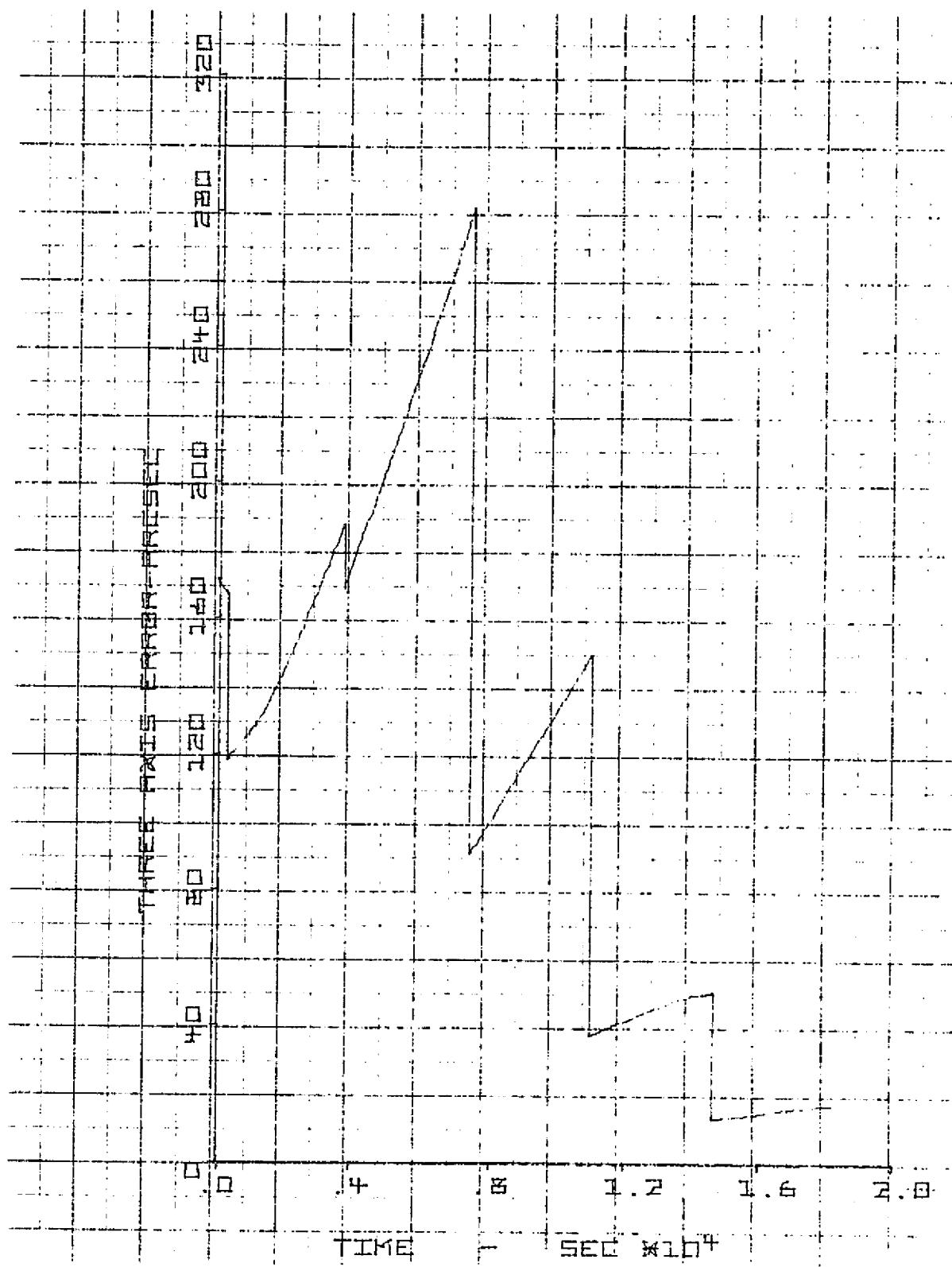


Figure 10-17. Pass No. 18 - Three Axis

10.3.5 PADS Accuracy

The criteria for the accuracy of the PADS is the mean difference between the PADS estimate of the inertial attitude of its reference axes and the true attitude of these axes as indicated by the laboratory instrumentation, and a priori knowledge of earth rate and the inertial attitude of the laboratory at the start of a test run. This criteria is designated σ_θ in Figures 10-8 and 10-13.

Tables 10-4 and 10-5 summarize the values of σ_θ for the two-axis and three-axis results. As mentioned previously, the first test run contained a z gyro malfunction and was not used. Also, only the fourth run was long enough to obtain a steady-state result for 60 minute updates. The n-axis RMS error divided by \sqrt{n} , is the PADS single-axis error.

The PADS design goal is 3.6 arc seconds (1σ) per axis for 20 minute star updates. The value of 3.6 arc seconds calculated from the two-axis results meets this goal, but the corresponding value of 4.8 arc seconds from the three-axis results does not. The poorer accuracy from the three-axis results is expected since the maximum angle between the three available stars was only 38 degree as compared to the optimum of 90 degrees. For the purpose of a comparison with the strapdown PADS, which did not have such a geometry constraint, the errors from the gimbal two-axis results will be used.

The two tables also show the increase in measured error with increased update interval. The inconsistency between the two-axis and three-axis trends is probably due to insufficient data points. The 23.3 arc seconds in Table 10-5 is definitely an anomalous point. No generalizations are apparent.

Table 10-4. PADS RMS Error μ_θ for Two-Axis Results

Test Run	20 Minute Updates	40 Minute Updates	60 Minute Updates
1	—	—	—
2	3.8	3.2	—
3	6.6	7.1	—
4	4.5	5.3	6.5
rms (2-axis)	5.1	5.4	6.5
rms (1-axis)	3.6 arc sec	3.8 arc sec	4.6 arc sec

Table 10-5. PADS RMS Error μ_θ for Three-Axis Results

Test Run	20 Minute Updates	40 Minute Updates	60 Minute Updates
1	—	—	—
2	7.3	4.6	—
3	8.6	23.3	—
4	8.9	6.6	15.0
rms (3-axis)	8.3	14.2	15.0
rms (1-axis)	4.8 arc sec	8.2 arc sec	8.7 arc sec

11. COMPONENT ACCURACIES

As a by-product of the system tests certain measurements of the performance of the individual star trackers and gyros were obtained. These measurements are presented in this section.

11.1 STRAPDOWN STAR TRACKER

As described in Section 4.3 the automatic autocollimator null bias was calibrated immediately before each star transit during a test run for the strapdown system test. This was accomplished by first pointing the parallel star and autocollimator beams at the theodolite, and then pointing them at the star tracker. While in the latter position, the tracker outputs as well as the autocollimator signals were stored on magnetic tape. Thus a measure of the boresight stability of the tracker was obtained before each star transit, i.e., every 20 minutes. Figure 11-1 is a plot of these measurements for the 12 star transits in the 1 October 1975 test run. Figure 11-2 is a plot of the mean of a run's measurements for the four runs made during the ten day test period. The fifth measurement in the plot was obtained from the initial data of a test run on 10 October 1975. This run was aborted due to an electronics failure in the data transmission equipment. The error shown in Figure 11-1 is probably due to the laboratory instrumentation errors. However, the error shown in Figure 11-2 does reflect the drift of the boresight over a ten day period since the run-to-run repeatability of the laboratory instrumentation is 0.6 arc second (3σ) (see Table 4-1).

In addition to the static boresight measurements, dynamic measurements of the star tracker accuracy were obtained for each star transit. The magnetic tape data from a test run was processed in an offline timeshare computer program. This program compared the compensated tracker outputs with the air bearing table compensated readout and prior knowledge of the star positions. The resulting error signal was passed through an RC filter with a 20 second time constant in order to smooth the tracker noise. Figure 11-3 through 11-14 are plots of the error signal for the 12 star transits of the 1 October 1975 test run. The beginning of the transit occurred on the right side of a plot, and the signal moved from right to left. This is evident in the vertical axis error signal of Figure 11-6 which shows two

sudden jumps in the data and their subsequent decays. The dynamic lag of the star tracker track loop is apparent in the horizontal axis error signal for all of the transits. The analytical calculation of this lag (Volume I) was 0.8 arc second, which is in good agreement with the plots. The star sequence for the 12 transits was 1,2,3,1,2,3, etc. Examination of the four plots for any particular star does not reveal a clear indication of a systematic error resulting from the polynomial compensation of the tracker output. This error is indistinguishable from the filtered tracker noise.

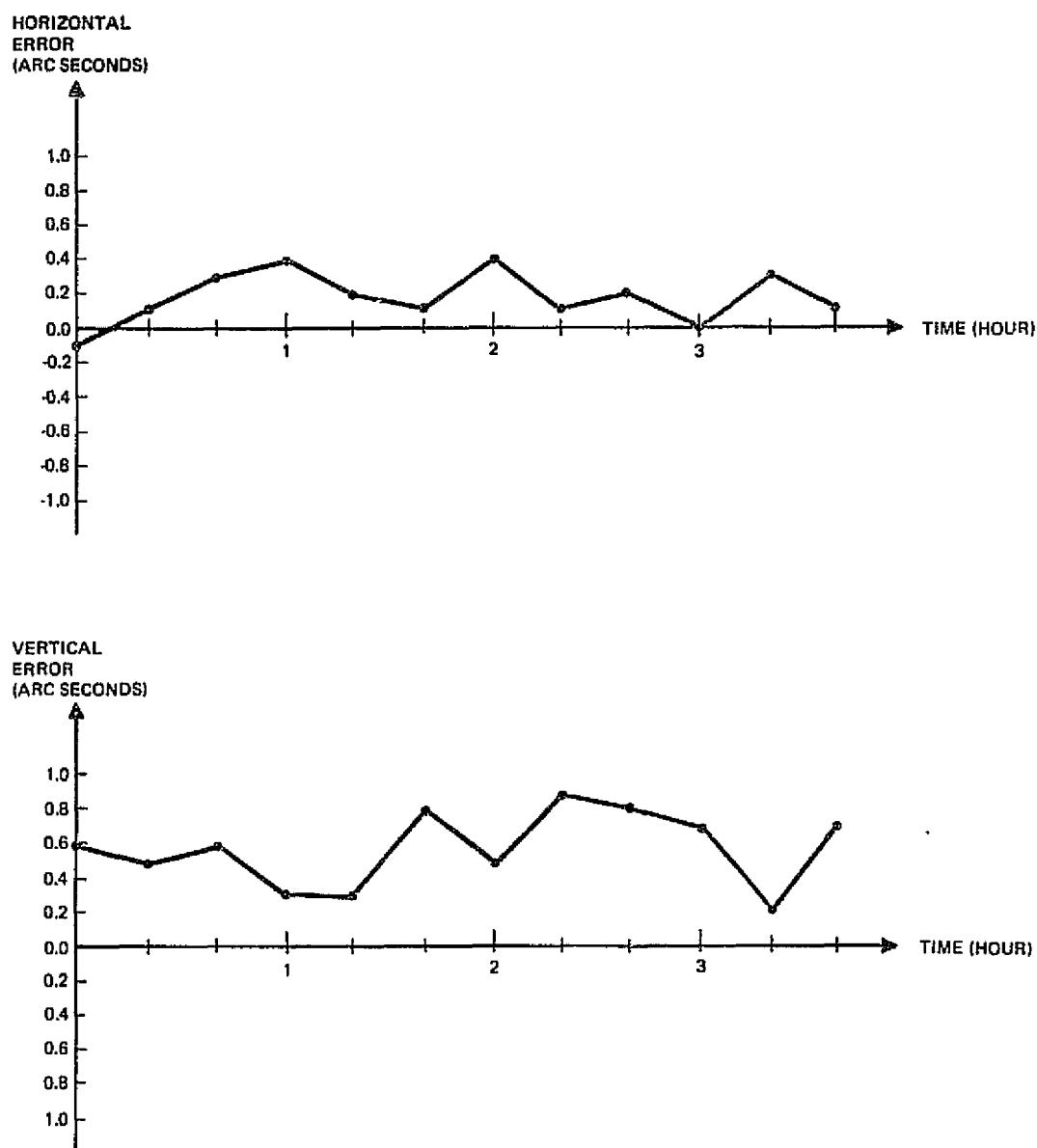


Figure 11-1. Static Boresight Error for 1 October 1975 Test Run

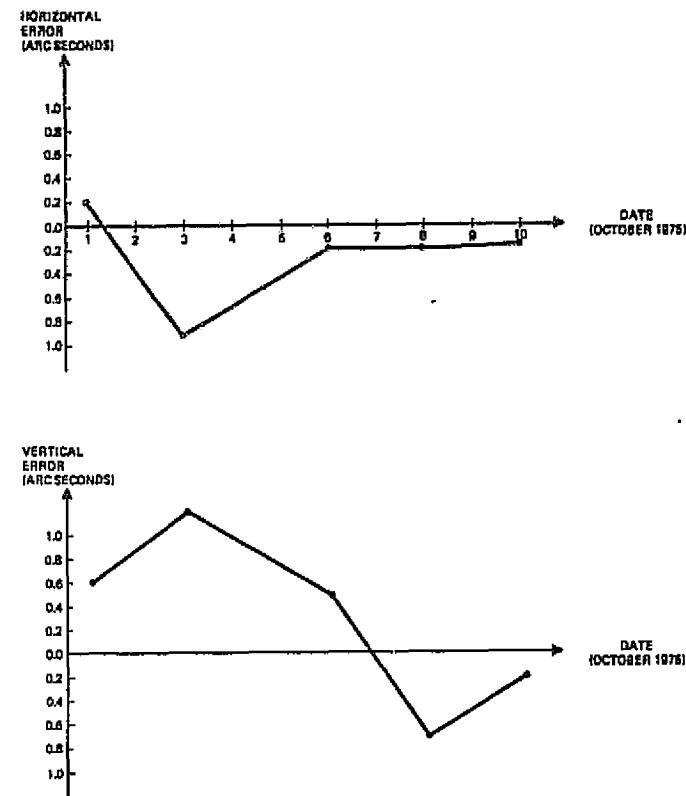


Figure 11-2. Mean Boresight Errors for Strapdown System Test

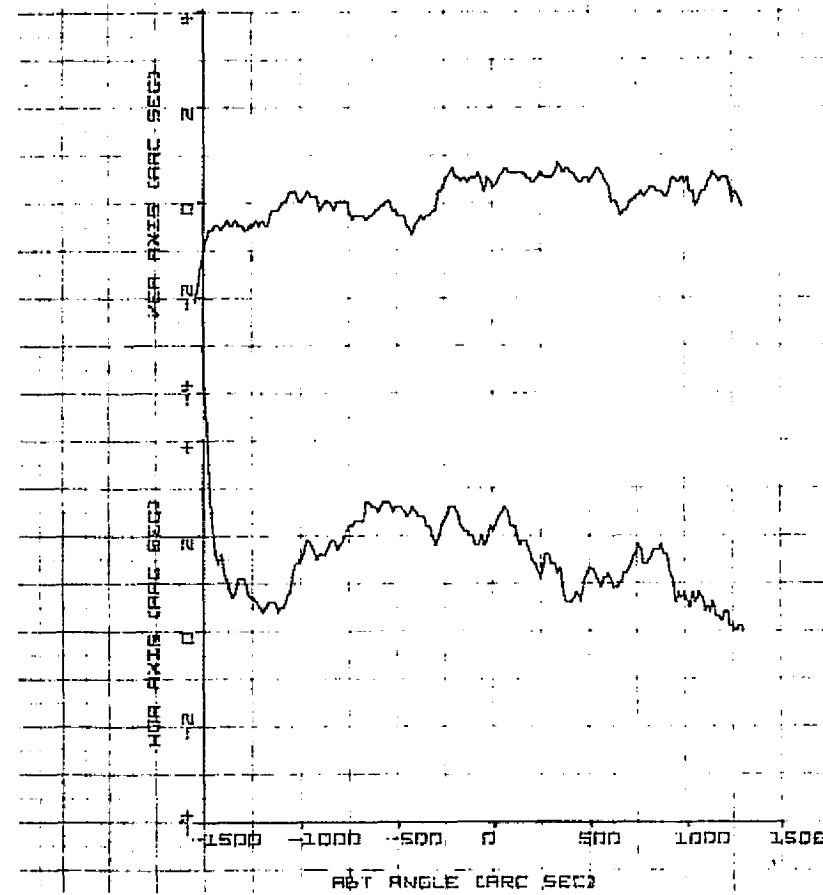


Figure 11-3. Star Transit Number 1

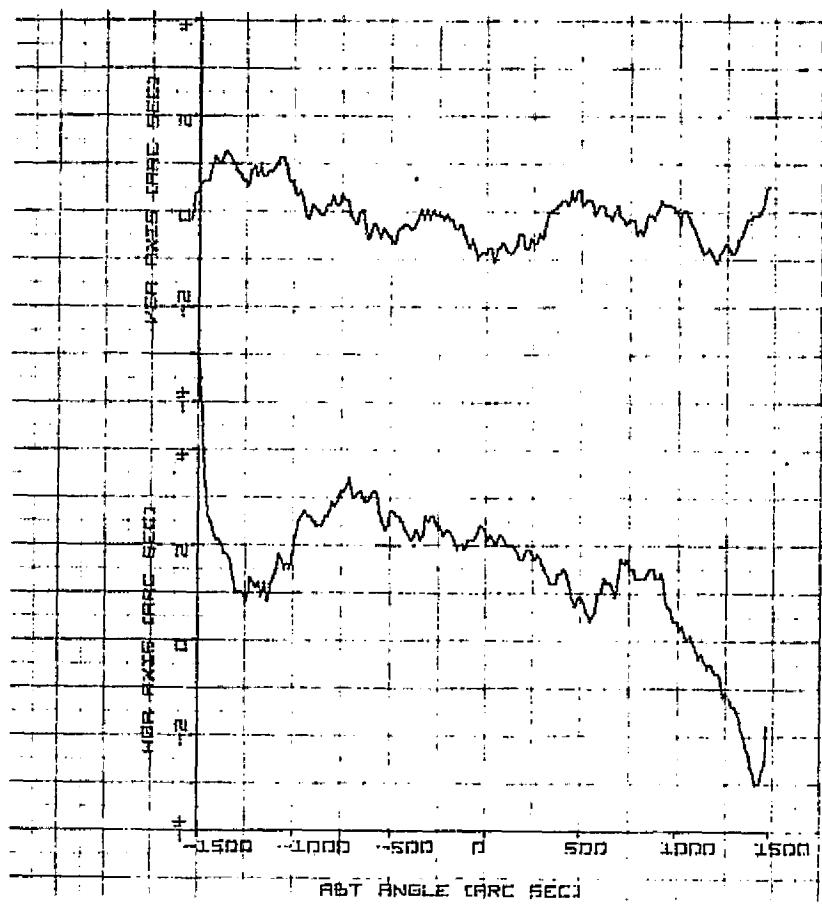


Figure 11-4. Star Transit Number 2

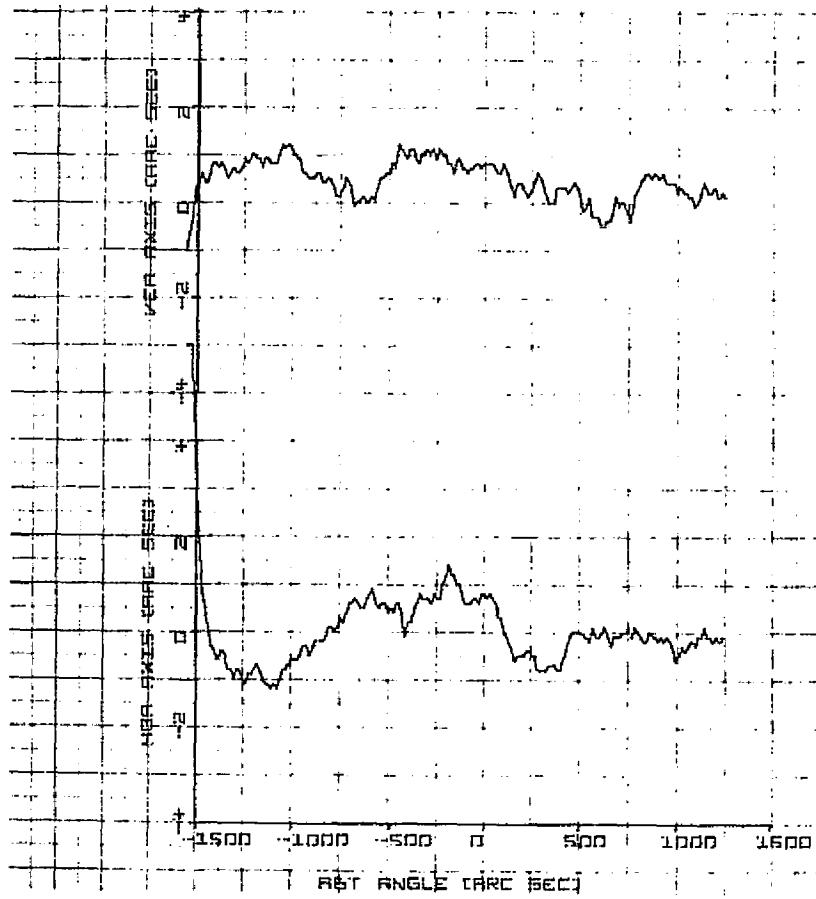


Figure 11-5. Star Transit Number 3

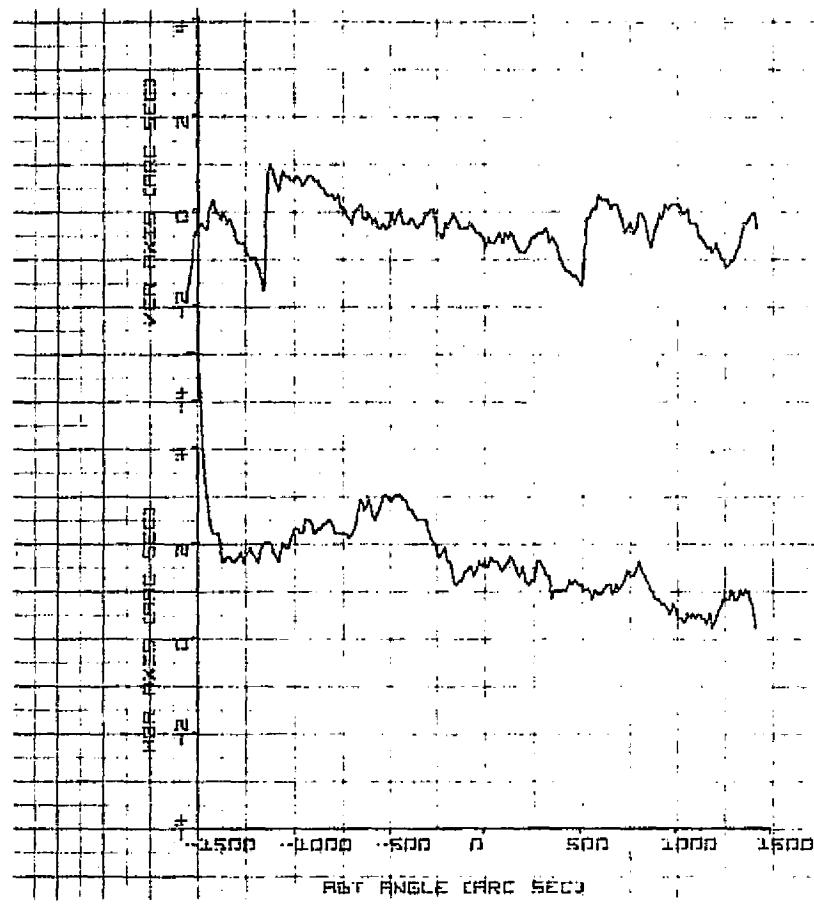


Figure 11-6. Star Transit Number 4

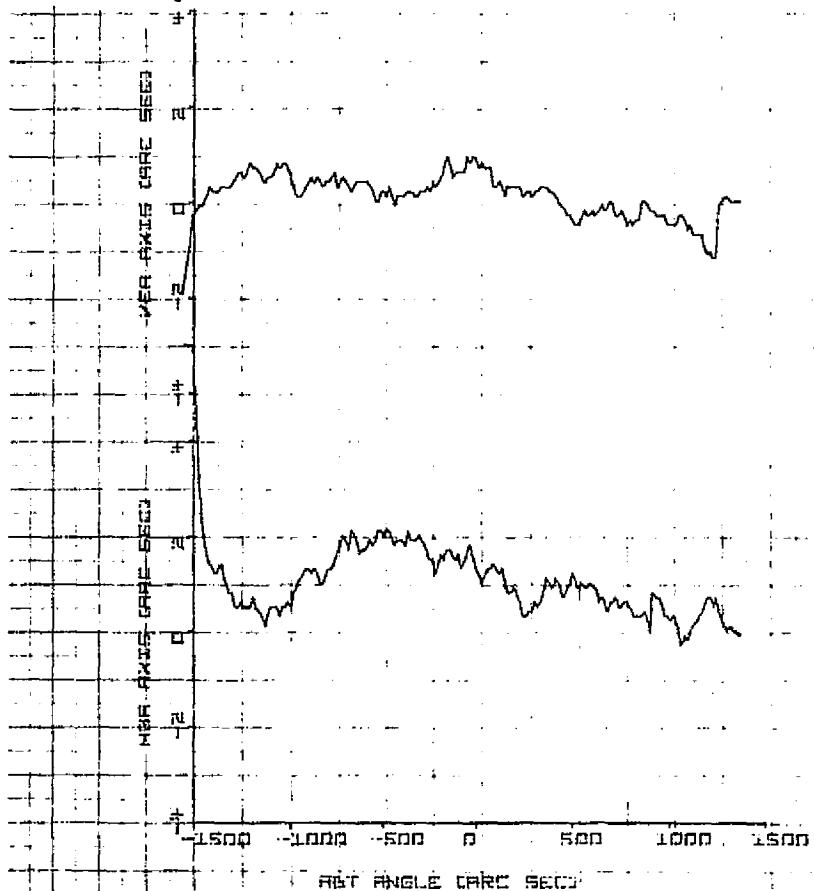


Figure 11-7. Star Transit Number 5

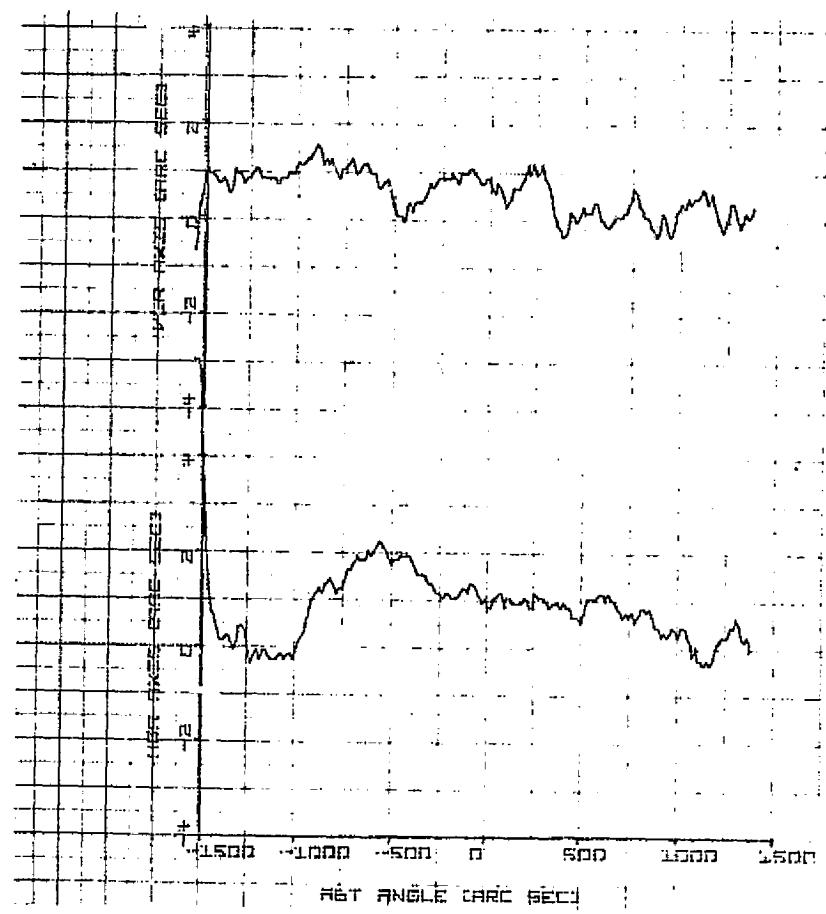


Figure 11-8. Star Transit Number 6

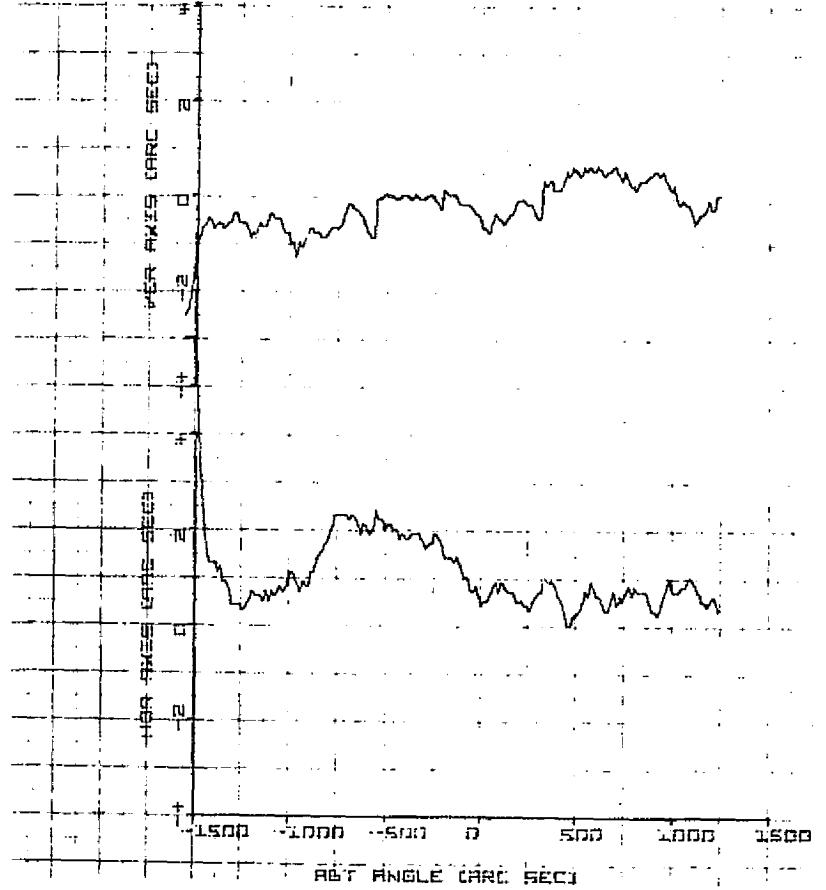


Figure 11-9. Star Transit Number 7

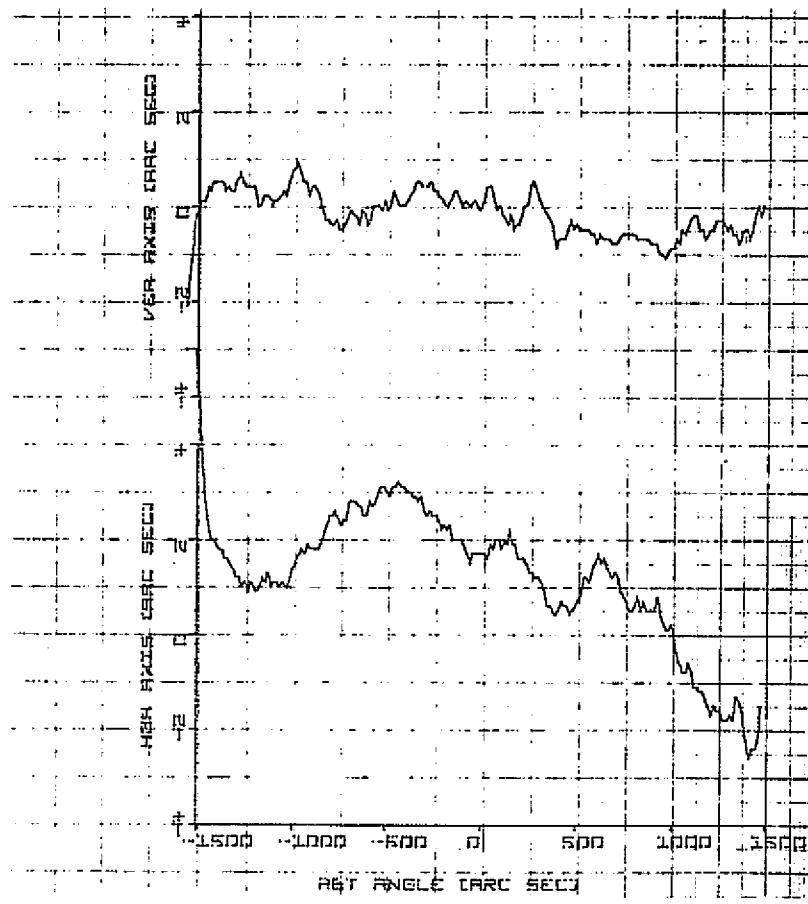


Figure 11-10. Star Transit Number 8

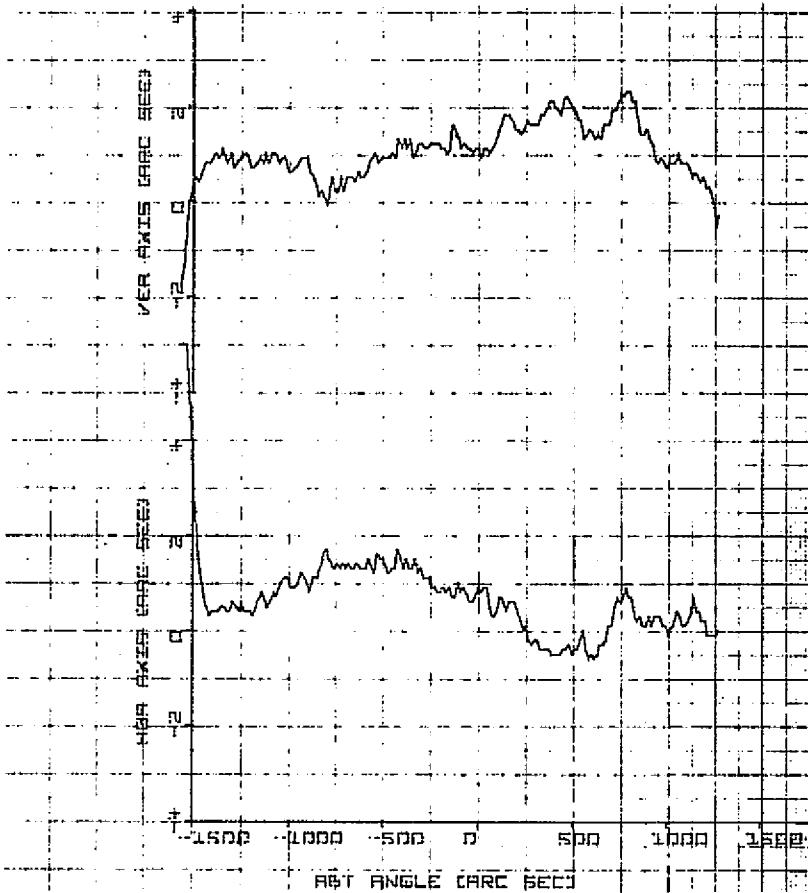


Figure 11-11. Star Transit Number 9

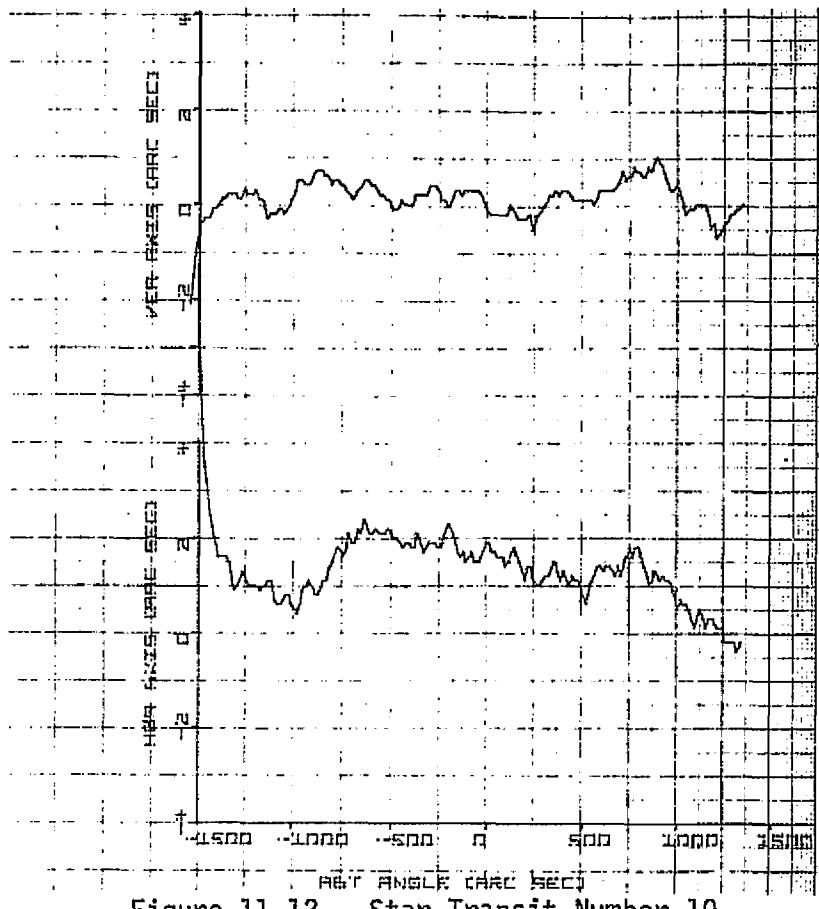


Figure 11-12. Star Transit Number 10

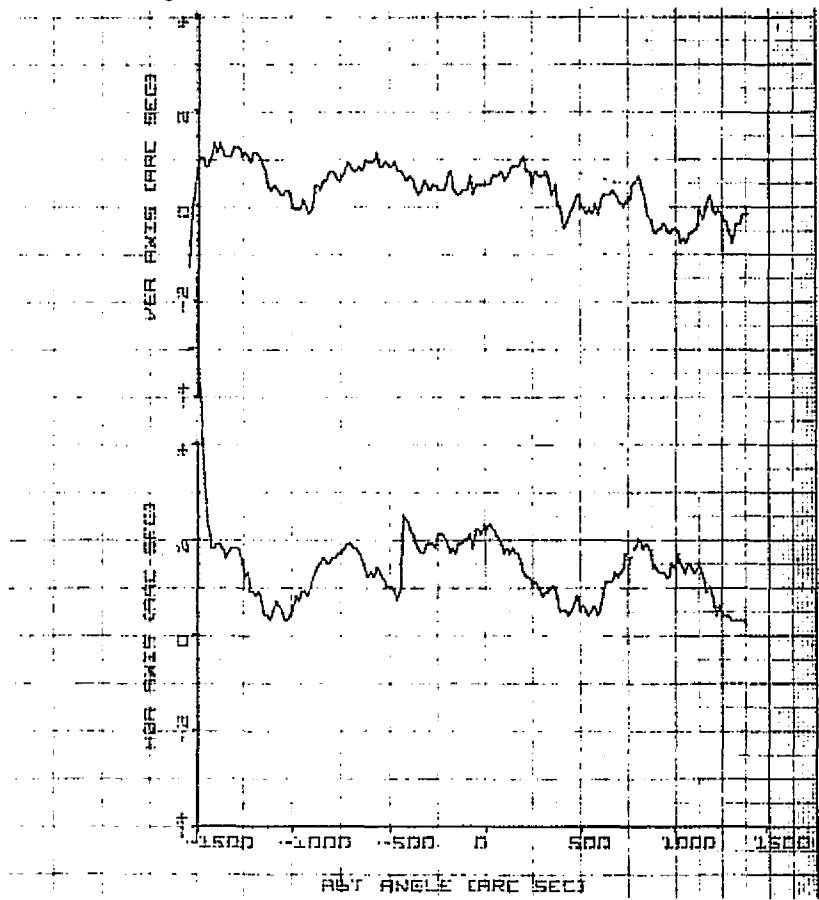


Figure 11-13. Star Transit Number 11

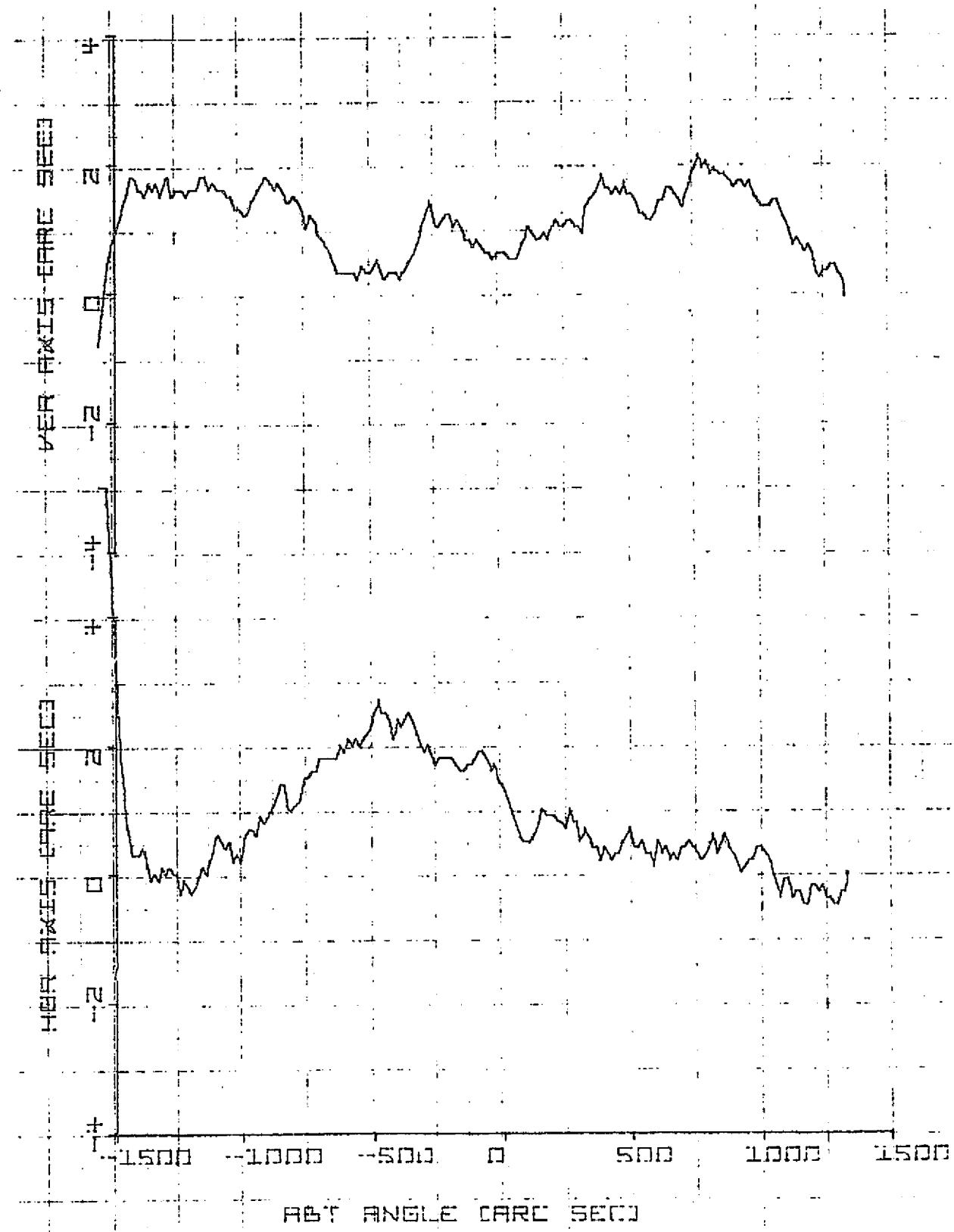


Figure 11-14. Star Transit Number 12

11.2 GIMBAL STAR TRACKER

The static boresight measurements recorded during the gimbal system test differed from those of the strapdown test in that each measurement was for one of the three different stars, not all for the middle star. The measured star positions immediately prior to the ten day system test are given in Section 4.1. The average deviations throughout a test run from these values are shown in Table 11-1 under the column absolute error. The table also lists the errors in the locations of the upper and lower stars relative to the center star.

Table 11-1. Static Boresight Errors for the Gimbal System Test

Test Run	Star	Absolute Error		Relative Error	
		AZ	EL	AZ	EL
8 Feb 76	1	-0.5	0.1	-0.4	0.0
	2	0.1	0.1	0.0	0.0
	3	0.4	-0.2	0.5	-0.3
9 Feb 76	1	1.8	-1.2	0.4	-0.4
	2	1.4	-0.8	0.0	0.0
	3	3.9	-0.9	2.5	-0.1
11 Feb 76	1	2.5	-0.1	0.2	-0.1
	2	2.3	0.0	0.0	0.0
	3	3.2	-0.5	0.9	-0.5
16 Feb 76	1	1.0	-0.4	-0.3	0.3
	2	1.3	-0.7	0.0	0.0
	3	1.9	-1.6	-0.6	-0.9

The relative errors are presented to indicate the accuracy of the laboratory instrumentation. These errors will be independent of bias shifts in either the optical sensor or the gimbal readout. With one exception, these errors support the accuracy assumed for the laboratory instrumentation. The exception is for star 3 azimuth during the 9 February 1976 run. Both the absolute and the relative errors appear off by 2.5 arc seconds. No explanation for this discrepancy was found. In general the absolute elevation

errors are small, while the azimuth errors are in the region of one to two arc seconds. These errors are believed to be indicative of the boresight stability of the tracker.

11.3 GYROS

The magnetic tape data for all eight test runs of both system tests was processed to indicate the drift stability of the gyros throughout a particular test run. Figures 11-15 through 11-22 show the attitude output stability of the three gyro axes for the eight test runs. The actual gyro output was a ramp function when plotted against time. In order to clearly show the ramp irregularities, the figures plot the output minus the ramp defined by the start and end points of the data.

In general the plots verify the performance measured previously for the gyros and presented in Appendix C. An exception, however, was the performance of the z gyro for the last three runs of the gimbal system test. Unexplainably, but fortuitously in view of the three-axis requirement of the test, the performance was much improved.

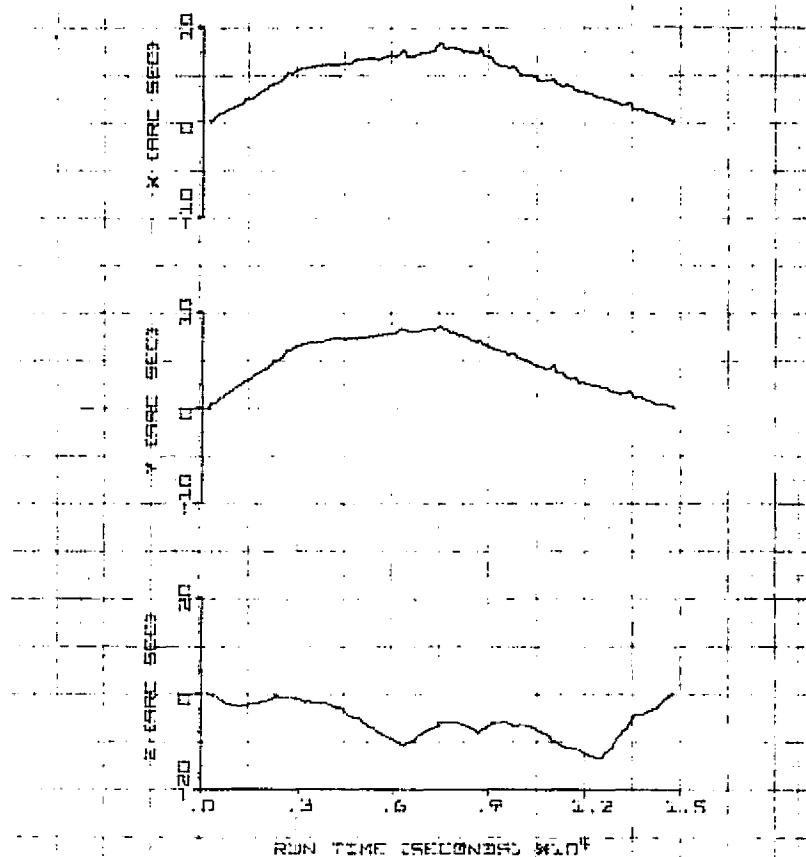


Figure 11-15. 10/01/75 Run

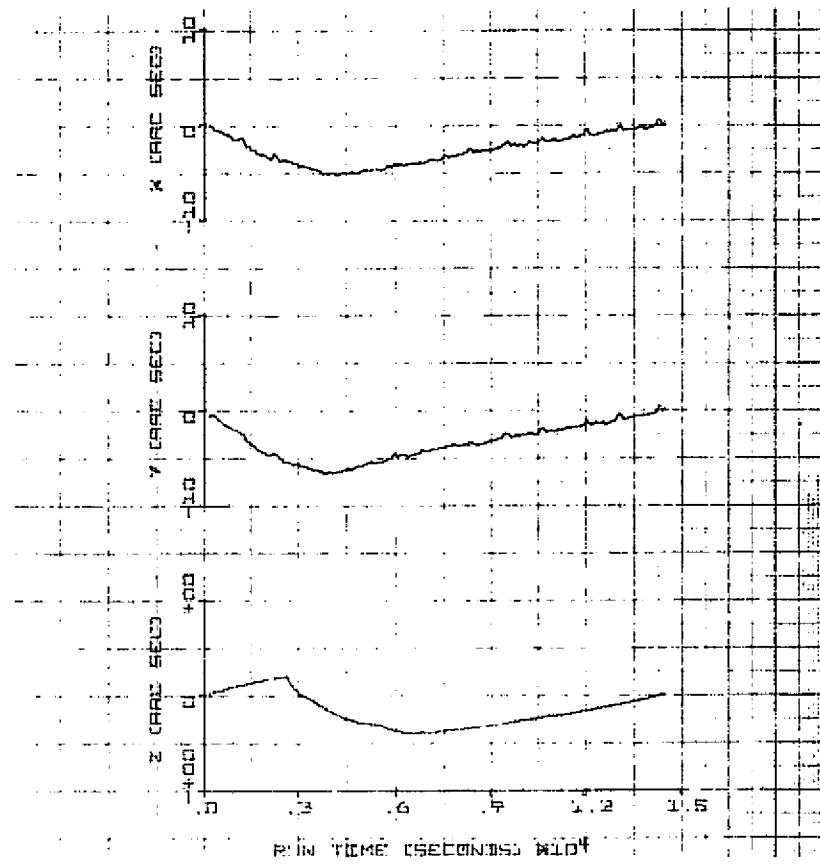


Figure 11-16. 10/03/75 Run

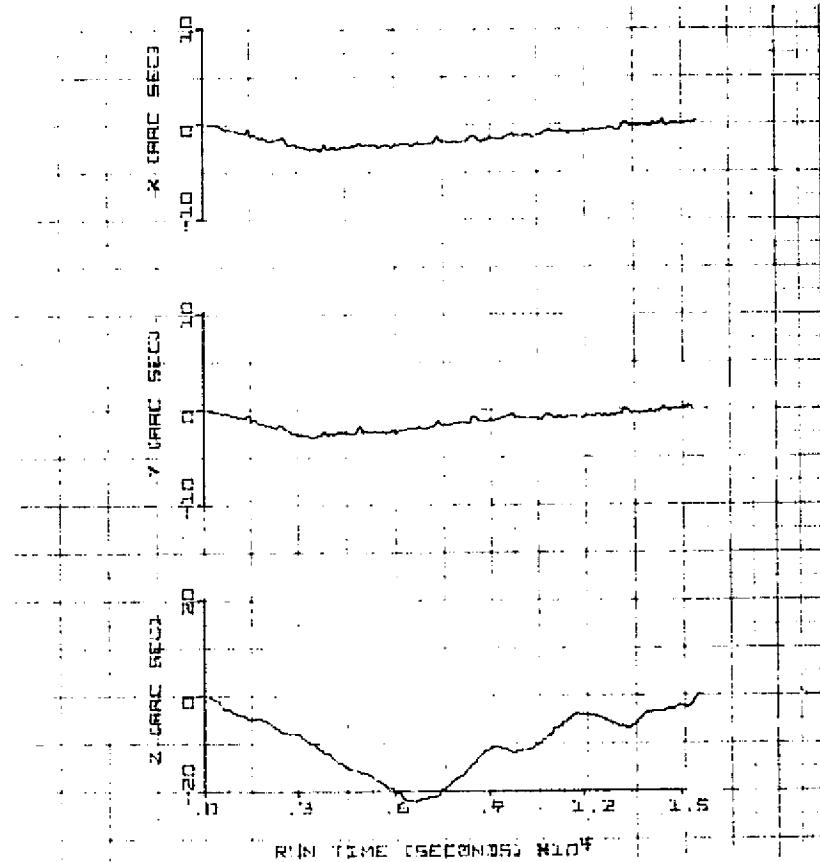


Figure 11-17. 10/06/75 Run

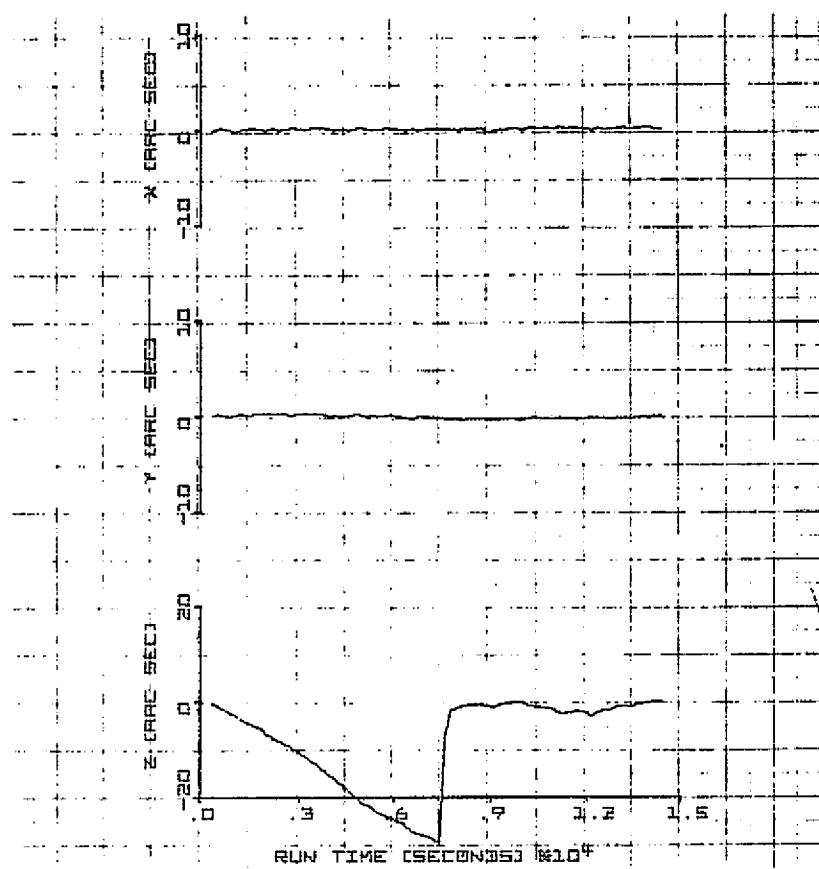


Figure 11-18. 10/08/75 Run

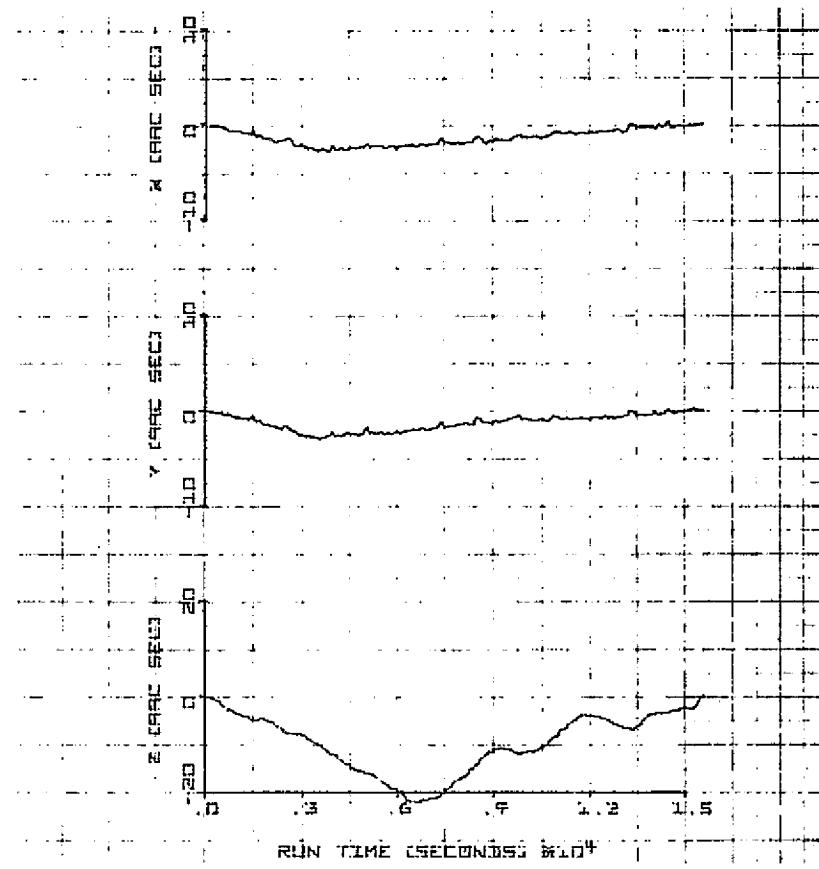


Figure 11-19. 02/06/76 Run

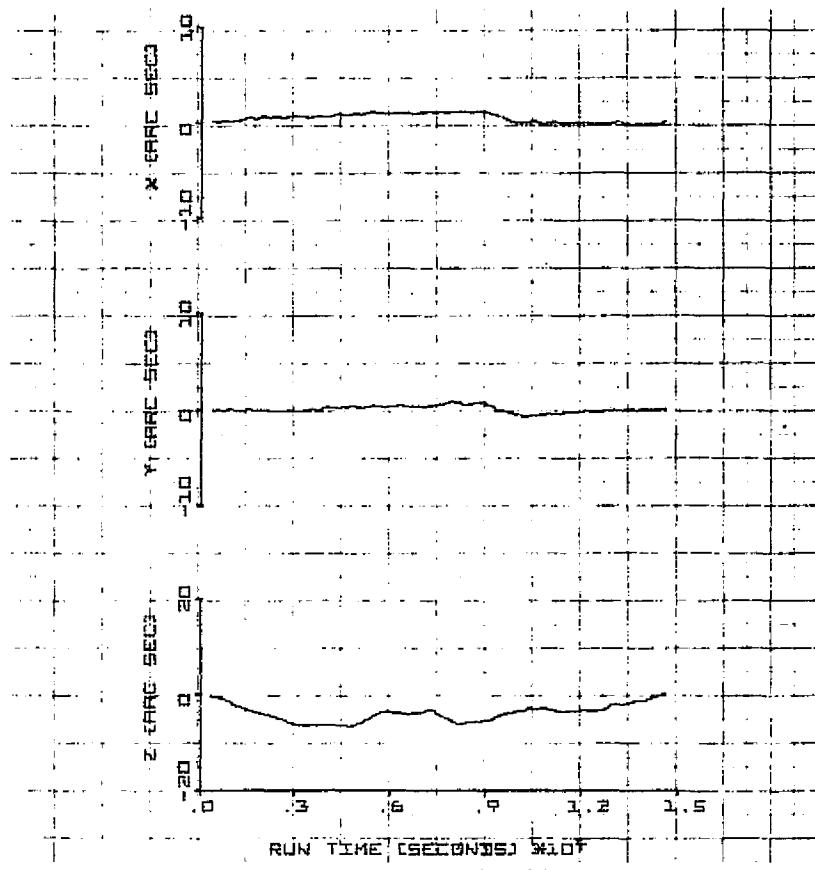


Figure 11-20. 02/09/76 Run

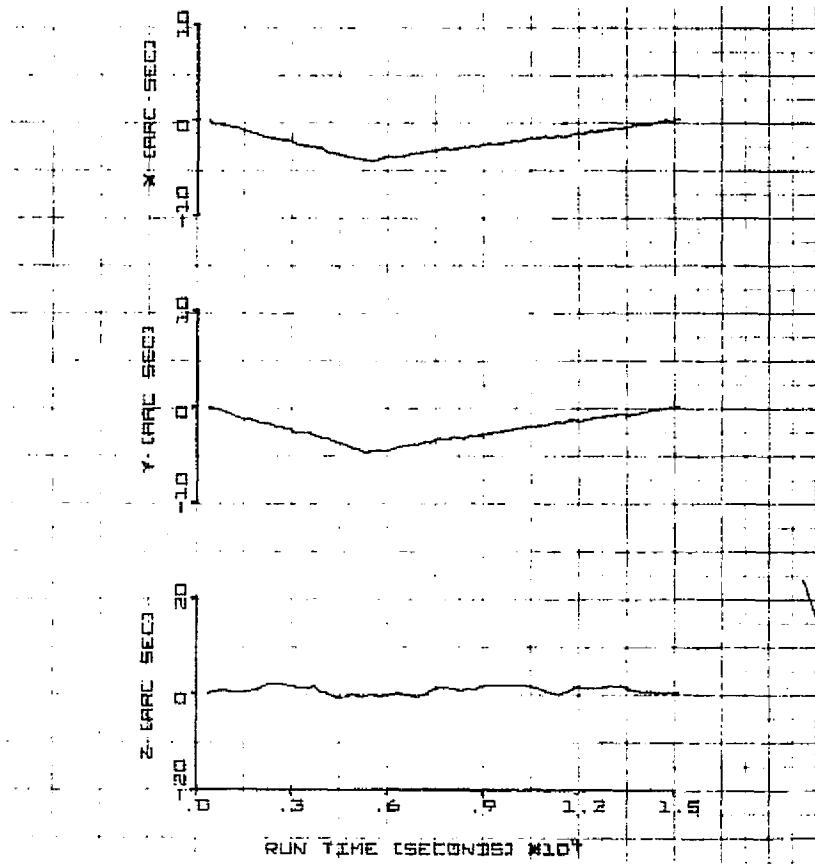


Figure 11-21. 02/11/76 Run

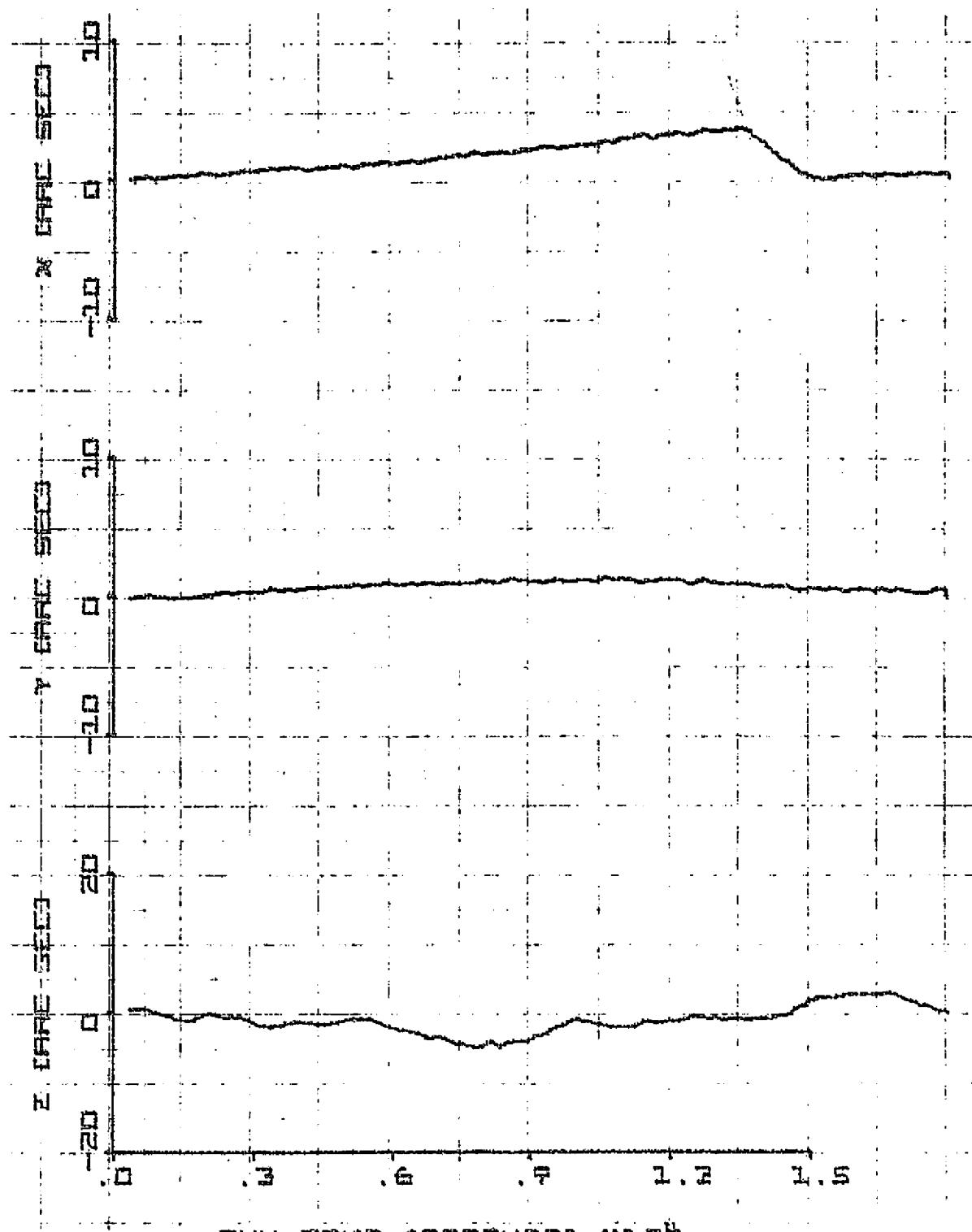


Figure 11-22. 02/16/76 Run

12. CONCLUSION

Both the strapdown and gimbal PADS met the accuracy goal of 3.6 arc seconds (1σ) per axis as demonstrated by the laboratory tests. The strapdown PADS accuracy of 2.3 arc second actually exceeded the goal by a convincing margin. The gimbal PADS accuracy of 3.6 just equaled the goal. It is noted that the gimbal accuracy was derived from the gimbal two-axis results which did not include the detrimental effect of the limited 38° separation between stars.

The laboratory tests have demonstrated that either system, under laboratory controlled temperature and vibration environments, will meet the design goal.

In a comparative sense, the performance of the strapdown system exceeds that of the gimbal system even more than the 20 minute update accuracies indicate. As pointed out in Section 4.1, for equal probabilities of star acquisition the gimbal tracker update interval should be 32 minutes if the strapdown tracker interval is 20 minutes. Although the quantitative effect of the longer update is not clear from the parametric results in Section 10.3.4, it is certain that the accuracy of the gimbal system will be even less for the longer update.

Also in a comparative manner, the alignment complexities associated with a test evaluation of the gimbal system, specifically the gimbal star tracker, are more numerous than those of a comparable strapdown system with two star trackers. These complexities arise primarily from the inability to directly identify the gimbal axis with an optical flat in the presence of a $1 g$ field. In another aspect, the hardware connected difficulties encountered with the gimbal star tracker provided a reminder of the comparative complexity of that unit relative to the strapdown star tracker.

The substitution of the OAO gyros for the originally intended Bendix gyros turned out well in that the anomalous behavior of the normally higher performance OAO gyros made their random drift rates comparable to those expected from the Bendix gyros. On the other hand, the drift rate variations of the x and y gyros were decidedly deterministic, displaying a

squarewave variation in rate which did not fit the assumed statistical models. Also, the performance of the z gyro was much poorer than either the z or y gyros, necessitating an artificial rotation of the gyro axes in the strapdown test to eliminate its effect from the two-axis results. It also invalidated one of the four gimbal test runs.

The attitude error convergence plots for both systems indicate that the limiting factor for the 20 minute update intervals is the star tracker error. The independent evaluations of the tracker noise and bias errors led to the conclusion that the software algorithms, and the Kalman filter in specific, did not add significantly to the total error. In this area the primary emphasis of the laboratory evaluations, namely, the star trackers and the algorithms, was fulfilled. However, the 40 and 60 minute update intervals presented a different case. Here the anomalous behavior of the gyros became dominant, and the Kalman filter understandably was unable to compensate for the sudden drift rate changes between star updates.

In terms of development status then, both star trackers have proven their performance capabilities and appear ready to proceed to flight level designs and environmental testing. The one reservation, however, involves the strapdown star tracker hysteresis described in Volume I. In many applications this effect is undesirable, and efforts are now underway to identify and eliminate it.

The results obtained in the area of minimizing the laboratory instrumentation errors justify the ground-fixed test configuration chosen for the system tests. The predicted instrumentation errors of 0.9 and 1.6 arc seconds for the strapdown and gimbal tests, respectively, most probably were achieved in view of the overall test results. The advantage of presenting PADS attitude errors as computed, without qualifications for hypothesized instrumentation errors, outweighs the subtle aspects involved with the ground-fixed configuration.

While the ground-fixed test configuration did minimize the instrumentation errors, it also made clear that the limit in test accuracy for star trackers and attitude determination systems was reached using commercially-available instrumentation. The most obvious limitation was the theodolite.

While the Kern DKM3 is one of the best, if not the best, such instrument available, obtaining better than 0.5 arc second accuracy with the instrument is doubtful. Another limitation is the parallelism and perpendicularity accuracies of mirror surfaces. Procurement of such mirrors with specifications below one arc second is not only costly but often beyond the capabilities of most optical suppliers. Stability and collimation accuracy of star sources is another limitation. Even with the thermally passive approach used in this program, material creep and long-term deformations will often require months of settling time after initial installation to achieve better than 1 arc second stability.

It seems clear that if star trackers or attitude determination systems with sub-arc second accuracies are developed, a significant increase in the cost of testing such units or systems will be experienced. A large part of the test cost will be the development and certification of the precision test instrumentation required.

REFERENCES

1. "Autonomous Navigation Technology - Phase I Final Report," TRW Report 23850-6023-TU-00, AF SAMSO, Contract No. F04701-73-C-0222, August 1974.
2. "PADS System Design and Analysis (Single-Axis Gimbal Star Tracker)," TRW Report 13900-6016-RU-00, NASA/GSFC, Contract No. NAS 5-2111, 1 July 1974.
3. "IRU (DAO) Systems Handbook," Charles Stark Draper Laboratory Report, Contract No. NAS 5-11002, May 1970.
4. Bendett, R.M., et al, "Test Evaluation of a High Performance Pulse Rebalanced Gyro for Strapdown IMU Applications," presented at The National Aerospace Meeting of the Institute of Navigation, 12 May 1975.
5. Popelka, M.F., and Ferren, F.R., "Astro-Azimuth Comparative Studies with Wild T3, Wild T4, and Kern DKM3 Theodolites," AIAA Paper No. 72-842, 14-16 August 1972.
6. Fondelli, M., "Examination of the Precision of Kern DKM3 Theodolites," Military Geographic Institute, Florence, Italy.
7. Farrenkopf, R.L., "Attitude Determination Software for HEAO," TRW Report HEAO-75-460-177, 10 April 1975.

APPENDIX A

**DATA ANALYSIS PROGRAM LISTING FOR THE
STRAPDOWN SYSTEM TEST**

```

00100      PROGRAM PADS(INPUT,OUTPUT,TAPE1,TAPE2,TAPE4,TAPE5)
00110      COMMON/1/NG,NDELP,NN1
00120      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4),KSKP
00130      COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
00140      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),QO(4,6),WR(3,2),RP(4,4)
00150      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
00160      COMMON/6/NTR,ICAT,NO,YL(2,2)
00170      COMMON/7/YD(2,2),Y(2,2),UL(15),AST(3,3,2),STR(3,2)
00180      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
00190      DIMENSION GYDAT(500,12),GX1(12),GX2(12),MSTR(12)
00192 C      KTyp=0 - REAL LAB ; KTyp=1 - GYROS REORIENTED;
00194 C      KTyp=2 - IDEAL GYROS
00200      DATA KTyp/1/
00203 C      MSTR(I) DENOTES WHETHER THE I TH VISIBLE STAR WILL BE USED
00204 C      FOR FILTERING; IF SG, MSTR(I)=1
00205      DATA (MSTR(I),I=1,12)/1,1,1,1,1,1,1,1,1,1,1,1/
00206      5 FORMAT(X,7HKTyp = ,I1/)
00210      1 CONTINUE
00212      N7*3
00220 C      REWIND TAPES
00230      REWIND 1
00240      REWIND 2
00250      REWIND 4
00255      REWIND 5
00256      WRITE(2,5) KTyp
00260 C      EFFECTIVELY ELIMINATE THE FIRST DATA LINE
00280      READ(4,2) (GYDAT(I,J),J=1,12)
00310      NN1=3
00320 C      READ IN AND PRINT OUT INITIAL VALUES, SYSTEM PARAMETERS AND RUN
00330 C      CONTROL CONSTANTS
00340      CALL INPUT
00350 C      INITIALIZE COUNTERS AND FLAGS
00360      NXc=KPR=NF=0
00370      IGY=500
00375      MT=0
00380      NO=1
00390      READ(4,2) (GX1(J),J=1,12)
00400 C      BEGINNING OF FILTER LOOP
00410 C      INITIALIZE STATE TRANSITION MATRICES PHI1 AND PHI2
00420      15 CONTINUE
00440      CALL ZERO
00460      20 CONTINUE

```

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

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00490 C INDEX, THEN TEST FOR WHETHER NEW FLIGHT GYRO DATA SHOULD BE READ
00500      IGY=IGY+1
00510      IF(IGY.E.500) GO TO 23
00520      IGY=1
00530      DO 24 I=1,500
00540      READ(4,2) (GX2(J),J=1,12)
00550      DLT=GX2(1)-GX1(1)
00560      GYDAT(I,1)=GX1(1)
00570      DO 17 K=2,4
00580 17   GYDAT(T,K)=(GX2(K)-GX1(K))/DLT*4.8481368E-6
00590      IF(KTYP.EQ.0) GO TO 25
00592      IF(KTYP.EQ.1) GO TO 26
00600      GYDAT(T,2)=-4.68164026E-5
00610      GYDAT(I,3)=-4.49498700E-5
00620      GYDAT(I,4)=4.57512760E-5
00622      GO TO 25
00623 26   CONTINUE
00624      GYDAT(I,2)=GYDAT(I,2)+4.26794875E-5
00625      GYDAT(I,3)=GYDAT(I,3)+2.11571588E-6
00626      GYDAT(I,4)=GYDAT(I,4)+1.97941384E-5
00630 25   CONTINUE
00640      DO 18 K=5,12
00650 18   GYDAT(T,K)=GX1(K)
00660      DO 19 K=1,12
00670 19   GX1(K)=GX2(K)
00680      IF(FDF,4) 23,24
00690 24   CONTINUE
00700 C FORMAT ? IS BELSKYS TAPE FORMAT
00710 2   FORMAT(X,F10.3,3(F12.1),F3,X,3(F7.1,X),4(F5.1,X))
00720 C FORM TIME AND INTEGRATION STEP
00730 23  CONTINUE
00740      DFLT=GYDAT(IGY,1)-TIME
00750      TIME=GYDAT(IGY,1)
00760      DO 33 I=1,NG
00770 33   WM(I)=GYDAT(IGY,I+1)
00890 C TEST FOR END OF RUN
00900      IF(TIME.LT.TF) GO TO 43
00910      STOP
00920 43  CONTINUE
00930 C ADVANCE STATE PRINT COUNTER
00940      NXC=NXC+1
00950 C COMPUTE ESTIMATED SPACECRAFT BODY ANGULAR RATES

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00960      CALL GYPCK
00970 C   COMPUTE ESTIMATED SPACECRAFT ATTITUDE
00980      CALL ATT
00990 C   TIME TO PRINT STATE
01000      IF(NXC.LT.NDELP) 44,81
01010      81  CONTINUE
01020 C   FORM ESTIMATED SPACECRAFT ATTITUDE DIRECTION COSINE MATRIX
01030      CALL TPNS
01060 C   PRINT ESTIMATED STATE
01070      CALL Y1PRNT
01140      NXC=0
01150 C   IF KPR=1, THIS PRINT FOLLOWED A FILTER OPERATION
01160      IF(KPR.EQ.1) 48,44
01170      48  KPR=0
01180      GO TO 15
01190      44  CONTINUE
01230 C   TEST IF TRACKER DATA IS PRESENT
01240      IF(GYDAT(IGY,5).GT.0.5) 60,52
01250      52  NF=-KSKP
01260      GO TO 20
01300      60  CONTINUE
01310      IF(GYDAT(IGY,5).LT.1.5) GO TO 601
01312      MT=MT+1
01320      DV1=GYDAT(IGY,11)
01330      DV2=GYDAT(IGY,12)
01340      601 CONTINUE
01350      NF=NF+1
01360      IF(NF.1T.1) GO TO 20
01362 C   TEST WHETHER THIS STAR IS ACCEPTABLE
01364      IF(MSTR(MT).NE.1) GO TO 52
01370      TU=GYDAT(IGY,6)-DV1
01380      TV=GYDAT(IGY,7)-DV2
01390      TA7=-.032P266874+SSV(4,1)*TU +SSV(5,1)*TU*TU +SSV(6,1)*TU**3
01400      1+SSV(7,1) *TV+SSV(8,1)*TV*TV +SSV(9,1)*TV**3
01410      2+SSV(10,1)*TU*TV +SSV(11,1) *TU*TU*TV+SSV(12,1) *TU*TV**2
01420      TFL=-.402691706+SSV(13,1) *TV+SSV(14,1) *TV*TV+SSV(15,1)
01430      1*TV**3+SSV(16,1) *TU+SSV(17,1) *TU*TU+SSV(18,1) *TU**3
01440      2+SSV(19,1) *TV*TU+SSV(20,1) *TU*TV**2+SSV(21,1) *TV*TU**2
01450      YL(1,2)=Y(1,2)
01460      YL(2,2)=Y(2,2)
01470      Y(1,2) =-TA7+4.84E136E1E-6
01480      Y(2,2) =TFL+.64E13681E-6

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01490 C     AIR BEARING TABLE ANGLE COMPUTATION
01500 TD=6.20561512E-4*GYDAT(IGY,8)
01510 FP1=-D.P+1.2*SIN(TD)+C.D*COS(TD)
01520 TBL=-(GYDAT(1GY,8)/2.-ER1)**4.84813681E-6-2.35619449
01530 TF(NF,F0,1) 62,61
01540 62 CALL STPCHK(TBL)
01550 61 CONTINUE
01560 C     COMPUTE INERTIAL STAR DIR. COS.
01570 CALL STARDG(STR(1,1),ICAT,TBL)
01580 C     COMPUTE EST. TRACKER OUTPUT
01590 CALL TRAC
01600 CALL TRCFLT
01610 IF(NF.LT.10) GO TO 20
01620 C     START FTLTFRING
01630 C     COMPUTE TRACKER MEASUREMENT RESIDUAL NO M
01640 W1=SQRT((YD(1,2)-YD(1,1))**2+(YD(2,2)-YD(2,1))**2)
01650 C     DOES IT FALL WITHIN AN ALLOWABLE ERROR
01660 IF(W1.LT..1) GO TO 70
01670 72 PRINT 3,W1
01680 3 FORMAT(20HMEASUREMENT ERROR IS,2X,E13.6,6H, PUNT)
01690 STOP
01700 70 CONTINUE
01705 WRITE(5,4) TIME,W1,N7
01706 4 FORMAT(2(2X,E13.6),2X,I1)
01710 CALL X1PPNT
01720 NF=-KSKP
01730 C     FORM STATE NOISE ERROR COVARIANCE MATRIX
01740 CALL QMAT
01750 C     ALTER STATE TRANSITION MATRIX TO DEAL WITH 3 RATHER THAN 4
01760 C     ATTITUDE VARIABLES
01770 CALL PRFIL
01780 C     PROPAGATE STATE ERROR COVARIANCE MATRIX
01790 CALL FILT
01795 CALL PPNT(1)
01800 C     FORM MEASUREMENT MATRIX
01810 CALL HMTRX
01820 C     FORM MEASUREMENT NOISE COVARIANCE MATRIX
01830 CALL RMAT
01840 C     APPLY KALMAN ALGORITHM
01850 CALL FFTLT
01860 C     UPDATE STATE
01870 CALL PRFL

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01880 C ADVANCE FILTER COUNTER
01890      NPC=NPC+1
01900 C TIME TO PRINT STATE ERROR COVARIANCE MATRIX
01910      IF(NPC-NFP) 15,c6,80
01920    80 CONTINUE
01930      CALL PPNT(1)
01940      KPR=1
01950      GO TO 81
01960      END
01970 C
01980 C
01990      SUBROUTINE TRNS
02000 C COMPUTE DIRECTION COSINES OF SPACECRAFT ATTITUDE RELATIVE TO
02010 C ATTITUDE PREFERENCE AXES(ECI COORDINATES)
02020      COMMON/2/TIME,TG,TF,DELT,KDELT,X1(4),XIL(4)
02030      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
02040      DIMENSION T(4,4)
02050 C TRANSFORM EULER SYMMETRIC PARAMETERS TO DIRECTION COSINES RELATIVE
02060 C TO ECI AXES
02070      DO 10 I = 1,3
02080      T(I,I) = X1(4)
02090    10 CONTINUE
02100      T(1,2)=X1(3)
02110      T(1,3)=-X1(2)
02120      T(1,4)=X1(1)
02130      T(2,3)=X1(1)
02140      T(2,4)=X1(2)
02150      T(3,4)=X1(3)
02160      T(2,1) = -T(1,2)
02170      T(3,1) = -T(1,3)
02180      T(3,2) = -T(2,3)
02190      T(4,1) = T(1,4)
02200      T(4,2) = T(2,4)
02210      T(4,3) = T(3,4)
02220      T(4,4) = -X1(4)
02230      DO 40 I=1,3
02240      DO 40 J=1,3
02250      B(I,J,1)=0.
02260      DO 40 K=1,4
02270      P(I,J,1)= B(I,J,1)+T(I,K)*T(K,J)
02280    40 CONTINUE
02290      RETURN

```

```

02300      END
02310 C
02320 C
03100      SUBROUTINE X1PRNT
03110 C      PRINTS ESTIMATED STATE VECTOR AND S/C ATTITUDE MATRIX
03120 COMMON/1/NG,NDELP,NN1
03130 COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
03140 COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
03150 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
03160 DIMENSION C(3,3),D(4)
03170 CA=206264.81
03175 N7=1
03180 C      PRINT HEADING AND TIME
03190      WPITE(2,30) TIME
03200      CALL LABATT
03210      DO 60 I=1,3
03220      DO 60 J=1,3
03230      C(I,J)=0.
03240      DO 60 K=1,3
03250      60 C(I,J)=C(I,J)+B(I,K,1)*B(J,K,2)
03260      D(1)=CA*C(2,3)
03270      D(2)=CA*C(3,1)
03280      D(3)=CA*C(1,2)
03290      D(4)=SQRT(D(1)**2+D(3)**2)
03300 C      PRINT ESTIMATED EULER PARAMETERS AND S/C AND LAB ATTITUDE MATRIX
03310      WRITE(2,20) (I,X1(I),B(I,1,1),B(I,2,1),B(I,3,1),
03320      1B(I,1,2),B(I,2,2),B(I,3,2),D(I),I=1,3)
03330      WPITE(2,22) X1(4) ,D(4)
03340      WRITE(5,23) TIME,D(4),N7
03350      23 FORMAT(2(2X,E13.6),2X,I1)
03390 C      PRINT HEADING
03400      WPITE(2,50)
03420      DO 45 I=1,NN1
03520      PIMU1A=CA*PIMU(I)
03530      WPITE(2,21) I,PIMU1A
03570      45 CONTINUE
03590      30 FORMAT(X///RH TIME = ,E16.9//30X,
03600      150HESTIMATED SPACECRAFT ATTITUDE RELATIVE TO ECI AXES//X,
03610      234ND.,X,11HEULER PARAM,12X,17HATTITUDE ESTIMATE,27X,
03620      312HLAB ATTITUDE,12X,12HR,P,Y,RSS ER//)
03630      20 FORMAT(X,I1,2X,F12.9,X,3(X,F12.9),2X,B(X,F12.9),2X,F9.2)
03640      22 FORMAT(X,1H4,2X,F12.9,03X,F9.2)

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```

03650 50  FORMAT(X/14X,26HESTIMATED GYRO BIAS VECTOR/)
03660 21  FORMAT(15X,I1,4X,E12.5)
03670      PRETURN
03680      END
03690 C
03700 C
03710      SUBROUTINE PRNT(K1)
03720      COMMON/1/NG,NDELP,NN1
03730      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
03740      COMMON/6/NTP,ICAT,NC,YL(2,2)
03750      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
03760      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
03770      DIMENSION PT(3,3),F(3,3),TP(3,3)
03775      N7=?
03780 C      PPINTS THE ERROR COVARIANCE MATRIX, UPPER LEFT 3 BY 3 IN
03790 C      SMALL ANGLE FORM
03800 C      SAVE UPPER 3 BY 3
03810      DO 40 I=1,3
03820      DO 40 J=1,3
03830 40  PT(I,J)=P(I,J)
03840 C      CONVERT UPPER 3 BY 3 OF P MATRIX TO SMALL ANGLE FORM
03850      F(1,1)=2.*((X1(4)+X1(1)**2/X1(4))
03860      F(1,2)=2.*((X1(3)+X1(1)*X1(2))/X1(4))
03870      F(1,3)=-2.*((X1(2)-X1(1))*X1(3)/X1(4))
03880      F(2,1)=-2.*((X1(3)-X1(2))*X1(1)/X1(4))
03890      F(2,2)=2.*((X1(4)+X1(2)**2/X1(4))
03900      F(2,3)=2.*((X1(1)+X1(2)*X1(3))/X1(4))
03910      F(3,1)=2.*((X1(2)+X1(1))*X1(3)/X1(4))
03920      F(3,2)=-2.*((X1(1)-X1(2))*X1(3)/X1(4))
03930      F(3,3)=2.*((X1(4)+X1(3)**2/X1(4))
03940      DO 70 I=1,3
03950      DO 70 J=1,3
03960      TP(I,J)=0.
03970      DO 70 K=1,3
03980 70  TP(I,J)=TP(I,J)+P(I,K)*F(J,K)
03990      DO 75 I=1,3
04000      DO 75 J=1,3
04010      P(I,J)=0.
04020      DO 75 K=1,3
04030 75  P(I,J)=P(I,J)+F(I,K)*TP(K,J)
04070      NA = NN1+3
04160 C      PPTNT HEADING

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04110    10 WRITE(2,1)
04120      1 FORMAT(1H1,50X,6HP MATRIX)
04130      DD 20 I=1,NA
04140      WRITE(2,3) I
04150      3 FORMAT(1RX,4HROW ,I2/)
04160 C      PRINT P MATRIX
04170      20 WRITE(2,30) (P(I,J),J=1,NA)
04180 30      FORMAT(3X,6F17.6)
04190      IF(K1.EQ.0) GO TO 44
04200 C      PRINT STAR NUMBER
04210      50 WRITE(2,45) ICAT
04220      45 FORMAT(1 7X,14HSTAR NUMBER = ,I3)
04230      TST2=ATAN2(YD(2,2),1.)
04240      TST1=ATAN2(YD(1,2)*COS(TST2),1.)
04250      TT=ATAN2(YD(2,1),1.)
04260      DEL2=(TST2-TT)*206264.81
04270      DEL1=(TST1-ATAN2(YD(1,1)*COS(TT),1.))*206264.81
04280      WRITE(2,60) TST1,DEL1,TST2,DEL2
04290      60 FORMAT(3X,37HTRACKER OUTPUT ANGLES AND MEAS. ERPCF/
04300      15X,7HAZIMUTH,2X,E11.4,5H RAD.,3X,F10.3,
04310      27H ARCSFC/6X,5HELEV ,3X,E11.4,5H RAD.,3X,F10.3,
04320      37H ARCSFC)
04330      44 CONTINUE
04340      AT=SQRT(P(1,1) + P(3,3))*206264.81
04350      WRITE(2,39) AT
04360      39 FORMAT(26H SQRT OF POINTING TRACE = ,F10.3,9H ARC SEC.)
04365      WRITE(5,8) TIME,AT,N7
04366      8 FORMAT(2(2X,E13.6),2X,I1)
04370      DT$PLAY AT
04380 C      RESTORE P MATRIX
04390      DD 43 I=1,3
04400      DD 43 J=1,3
04410      43 P(I,J)=PT(I,J)
04420      RETURN
04430      END
04440 C
04450 C
04930      SUBROUTINE INPUT
04940 C      READS IN AND PRINTS INITIAL VALUES, SYSTEM PARAMETERS, RUN CONTROL
04950 C      CONSTANTS, AND CONVERTS SPECIFIED ANGLES TO RADIANS
04960 C      COMMON/1/NG,NDELP,NN1
04970 C      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),XIL(4),KSKP

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04980 COMMON/3/PTMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
04990 COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WF(3,2),RP(4,4)
05000 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
05010 COMMON/6/NTR,ICAT,NG,YL(2,2)
05020 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
05030 COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
05040 DIMENSION NSV(4,32),C(3,3),T(3)
05050 NN=NN+3
05060 DO 112 I=1,NN
05070 DO 112 J=1,NN
05080 112 P(I,J)=0(I,J)=C.
05090 C READ INPUT FLAGS DEFINING TYPE OF RUN AND PRINT OPTIONS
05100 READ(1,2) NTR,NG
05110 2 FORMAT(I1)
05120 READ(1,3) NDELP,KSKP
05130 3 FORMAT(I3)
05150 C READ NOMINAL STAR TRACKER TRANSFORMATION MATRIX
05160 DO 20 K=1,NTR
05170 20 READ(1,4) ((AST(I,J,K),J=1,3),I=1,3)
05180 4 FORMAT(F9.6)
05200 C READ STAP SENSOR PARAMETERS
05210 DO 24 J=1,NTR
05220 READ(1,6) (SSV(I,J),I=1,21)
05230 24 READ(1,5) (SSV(I,J),I=22,27)
05240 5 FORMAT(F9.3)
05250 C READ GYRO PARAMETERS
05260 DO 25 J=1,NC
05270 25 READ(1,6) (GY(I,J),I=1,9)
05280 C READ ESTIMATED INITIAL RATES
05300 DO 27 I=1,3
05310 27 READ(1,6) PP(I)
05330 6 FORMAT(F12.6)
05340 C READ INITIAL 4 PARAMETER ATTITUDE
05350 READ(1,4) (X1(I),I=1,4)
05360 22 CONTINUE
05370 C READ INITIAL AND FINAL TIMES AND INTEGRATION STEP SIZE
05380 READ(1,6) T0,TF,DELT
05390 C READ ERROR COVARIANCE INITIAL DIAGONAL ELEMENTS
05400 C UNITS ARE RAD.,SEC
05410 DO 28 I=1,NN
05420 28 READ(1,6) P(1,I)
05470 C

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05490 C      TEMPORARY INPUT PRINT ROUTINE
05500          WPITE(?,12)
05510    12  FORMAT(1H1)
05520          WPITF(2,7) NTR,NG,NDELP
05540    7   FORMAT( 3(X,I3)//)
05560          DD 31 J=1,NC
05570    31  WRITE(2,8) (GY(I,J),I=1,9)
05580    8   FORMAT(9(X,F10.3))
05590          WRITE(2,10)
05600    10  FORMAT(/)
05610          DD 32 K=1,NTR
05620    32  WRITE(2,9) ((AST(I,J,K),J=1,3),I=1,3)
05630    9   FORMAT(9(X,F9.6))
05640          WRITF(2,10)
05650          DD 34 J=1,NTK
05670    34  WRITE(2,11) (SSV(I,J),I=1,27)
05680    11  FORMAT(9(X,E10.3))
05690          WRITF(2,10)
05700          DD 35 J=1,3
05720    35  WPITF(2,R) PP(J)
05730    41  CONTINUE
05740          WPITE(2,10)
05760          WRITE(2,R) (X1(I),I=1,4)
05770          WRITE(2,10)
05780          DD 37 K=1,NN
05790    37  WPITF(2,R) P(K,K)
05800          WPITF(2,10)
05810          WRITE(2,R) TO,TF,DELT
05820          WRTTE(2,10)

05880 C
05890 C      INITIALIZE PROBLEM TIME
05900          TIME = TO
05910    15  FORMAT(1H1)
05920          WPITE(2,15)
05930 C      CONVERT ANGLES TO RADIANS
05940          CF = 4.8481306E-06
05950          CFSQ = CF*CF
05970          DD 130 J=1,NTR
05980          SSV(24,J)=SSV(24,J)*CF
05990          SSV(25,J)=SSV(25,J)*CF
06000    130 CONTINUE
06020          DD 135 J=1,NG

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06030      GY(1,J)=GY(1,J)*CF
06040      DO 135 T=7,9
06050      GY(I,J)=GY(T,J)*CF
06060 135 CONTINUE
06070      CALL TINITIAL
06080 C      PRINT FRRDP COVARIANCE MATRIX
06090      CALL PRNT(0)
06100 C      PRINT INITIAL STATE VECTOR
06110      CALL TRNS
06130      CALL XIPRNT
06180      RETURN
06190      END
06200 C
06210 C
06220      SUBROUTINE ZERO
06230 C      INITIALIZES STATE TRANSITION MATRICES PHI1 AND PHI2 AFTER EACH
06240 C      FILTER UPDATE
06250      COMMON/1/NG,NDELP,NN1
06260      COMMON/2/T0,TF,DELT,KDELT,X1(4),XIL(4)
06270      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
06280 C      RETAIN FILTER UPDATED VALUES OF EULER PARAMETERS FOR NEXT FILTER
06290 C      OPERATION
06300      DO 21 I=1,4
06310      XIL(I)=X1(I)
06320 C      SET PHI1 ELEMENTS EQUAL TO ZERO
06330      DO 22 J=1,4
06340      PHI1(I,J)=0.
06350 22 CONTINUE
06360 C      SET PHI2 ELEMENTS EQUAL TO ZERO
06370      DO 23 J=1,NN1
06380      PHI2(I,J)=0.
06390 23 CONTINUE
06400 C      SET PHT1 DIAGONAL ELEMENTS EQUAL TO ONE
06410      PHI1(T,T)=1.
06420 21 CONTINUE
06430 C      SET Q MATRIX COMPUTATION INTERVAL COUNTER TO ZERO
06440      KDELT=0
06450 C      SET C MATRIX ELEMENTS TO ZERO
06460      DO 10 T=1,7
06470      DO 10 J=1,7
06480 10  O(T,J)=0.
06490      RETURN

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06500      END
06510 C
06520 C
06530      SUBROUTINE INITIAL
06540      COMMON/1/NG,NDELP,NN1
06550      COMMON/2/TIME,TO,TF,DEL1,KDELT,X1(4),X1L(4)
06560      COMMON/3/PTMUI(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
06570      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),QO(4,6),WR(3,2),RP(4,4)
06580      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
06590      COMMON/6/MTR,ICAT,NO,YL(2,2)
06600      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
06610      DIMENSION TP1(3,3),TP2(3,3),TP3(3,12),TP4(6,3)
06620 C      COMPUTE GYRO WEIGHTING MATRIX, TAU
06630      DO 12 I=1,NG
06640      DO 12 J=1,3
06650 12   TP4(I,J)=(1.+GY(2,I))*GY(3+J,I)
06660      DO 10 I=1,3
06670      DO 10 J=1,3
06680      TP1(I,J)=0.
06690      DO 10 K=1,NG
06700      TP1(J,K)=TP1(I,J)+TP4(K,I)*TP4(K,J)
06710 10   CONTINUE
06720      DEL=TP1(1,1)*TP1(2,2)*TP1(3,3)+TP1(1,2)*TP1(2,3)*TP1(3,1)
06730      1+TP1(1,3)*TP1(2,1)*TP1(3,2)-TP1(1,3)*TP1(2,2)*TP1(3,1)
06740      2-TP1(1,1)*TP1(2,3)*TP1(3,2)-TP1(1,2)*TP1(2,1)*TP1(3,3)
06750      DL=1./DEL
06760      TP2(1,1)=(TP1(2,2)*TP1(3,3)-TP1(3,2)*TP1(2,3))*DL
06770      TP2(1,2)=(TP1(3,2)*TP1(1,3)-TP1(1,2)*TP1(3,3))*DL
06780      TP2(1,3)=(TP1(1,2)*TP1(2,3)-TP1(2,2)*TP1(1,3))*DL
06790      TP2(2,1)=(TP1(3,1)*TP1(2,3)-TP1(2,1)*TP1(3,3))*DL
06800      TP2(2,2)=(TP1(1,1)*TP1(3,3)-TP1(1,3)*TP1(3,1))*DL
06810      TP2(2,3)=(TP1(2,1)*TP1(1,3)-TP1(1,1)*TP1(2,3))*DL
06820      TP2(3,1)=(TP1(2,1)*TP1(3,2)-TP1(3,1)*TP1(2,2))*DL
06830      TP2(3,2)=(TP1(3,1)*TP1(1,2)-TP1(1,1)*TP1(3,2))*DL
06840      TP2(3,3)=(TP1(1,1)*TP1(2,2)-TP1(2,1)*TP1(1,2))*DL
06850      DO 15 I=1,3
06860      DO 15 J=1,NG
06870      TAU(I,J)=0.
06880      DO 15 K=1,3
06890      TAU(I,J)=TAU(I,J)+TP2(I,K)*TP4(J,K)
06900 15   CONTINUE
06910 C      INTITALIZE PAST DATA

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06930      D7 20 I=1,NG
06940      D7 20 J=1,2
06950  20  D9FT(I)=GY(1,I)
06960      D7 30 I=1,3
06980  30  WP(I,1)=WR(I,2)=PP(I)
06990 C   COMPUTE INITIAL GYRUPACK PARAMETERS, PIMU
07010      D7 40 I=1,3
07020      PTMU(I)=0.
07030      D7 40 J=1,NG
07040      PIMU(I)=PTMU(I)+TAU(I,J)*(1.+GY(2,J))*GY(1,J)
07050  40  CONTINUE
07070      L=3
07080      D7 50 J=1,3
07090      D7 60 J=1,3
07100      L=L+1
07110      PTMU(L)=0.
07120      D7 60 K1=1,NG
07130      PIMU(L)=PIMU(L)+TAU(I,K1)*(1.+GY(2,K1))*GY(3+J,K1)
07140  60  CONTINUE
07150      PIMU(4*I)=PIMU(4*I)-1.
07160  50  CONTINUE
07170 C   COMPUTE TAU*TAU-T*SIG-SQ FOR USE IN Q
07180      D7 65 J=1,NG
07190      TP3=SQRT(GY(7,J)**2*100.00*DELT+GY(9,J)**2) /100./DELT
07200      D7 65 I=1,3
07210      TP(T,J+6)=TAU(I,J)*GY(6,J) *SQRT(100.*DELT)
07220  65  TP(I,J)=TAU(I,J)*TP3
07230      D7 70 I=1,3
07240      D7 70 J=1,3
07250      OO(I,J)=0.
07260      OO(I,J+3)=0.
07270      D7 70 K=1,NG
07280      OO(I,J+3)=OO(I,J+3)+TP(I,K+6)*TP(J,K+6)
07290  70  OO(T,J)=OO(T,J)+TP(I,K)*TP(J,K)*2500.*DELT*DELT
07370 C   CONVERT UPPER LEFT 3 BY 3 OF P MATRIX TO EULER SYMMETRIC
07380 C   PARAMETER FORM. ORIGINAL P ASSUMED DIAG. TAL.
07390      Z1=P(1,1)
07400      Z2=P(2,2)
07410      Z3=P(3,3)
07420      P(1,1)=.25*(Z1*X1(4)**2+Z2*X1(3)**2+Z3*X1(2)**2)
07430      P(1,2)=P(2,1)=.25*((Z1-Z2)*X1(4)*X1(3)-Z3*X1(1)*X1(2))
07440      P(1,3)=P(3,1)=.25*((Z3-Z1)*X1(4)*X1(2)-Z2*X1(1)*X1(3))

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07450 P(2,2)=.25*(L1*X1(3)**2+Z2*X1(4)**2+Z3*X1(1)**2)
07460 P(2,3)=P(3,2)=-.25*((L2-Z3)*X1(1)*X1(4)-L1*X1(2)*X1(3))
07470 P(3,3)=.25*(L1*X1(2)**2+Z2*X1(1)**2+Z3*X1(4)**2)
07600 RETURN
07610 END
07620 C
07630 C
07640 SUBROUTINE STARCHK(TBL)
07650 COMMON/1/NG,NDELP,NN1
07660 COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
07670 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
07680 COMMON/6/NTR,ICAT,NU,YL(2,2)
07690 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
07700 DIMENSION TP(3),A(3,3)
07710 T=0
07720 CP=10.
07730 40 J=I+1
07740 IF(I.GT.3) GO TO 100
07750 C FORM STAR I INERTIAL DIR.COS.
07760 CALL STARD(C(STR(1,1),I,TBL))
07770 C FORM STAR DIR. COS. IN STA AXES
07780 DO 50 K=1,3
07790 U(K)=0.
07800 DO 50 J=1,3
07810 50 U(K)=U(K)+B(K,J,1)*STR(J,1)
07820 C FORM MEAS. RESIDUAL
07830 PR=(Y(1,2)+U(1)/U(2))**2+(Y(2,2)-U(3)/U(2))**2
07840 IF(PR.GT.CP) GO TO 40
07850 CR=PR
07860 ICAT=I
07870 GO TO 40
07880 100 CONTINUE
07890 YL(1,1)=YL(1,2)=Y(1,1)=YD(1,1)=YD(1,2)=Y(1,2)
07900 YL(2,1)=YL(2,2)=Y(2,1)=YD(2,1)=YD(2,2)=Y(2,2)
07910 RETURN
07920 END
07930 C
07940 C
07950 SUBROUTINE STARD(C,ISTR,TBL)
07960 COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
07970 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
07980 DIMENSION C(3),TR(3,3),RN(3),D(3)

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C-3

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07990 C  DEFINE STAR DIR. COS. IN LAB(STA) AXES
08000     TP(1,1)=1.
08010     TP(1,2)=TP(1,3)=0.
08020     TP(2,1)=.9999902
08030     TP(2,2)=2.424E-6
08040     TP(2,3)=4.41956E-3
08050     TP(3,1)=.9999986
08060     TP(3,2)=-2.424E-6
08070     TP(3,3)=-1.580493E-3
08080     CALL TPMS
08090 C  FORM MIRROR OUTWARD NORMAL
08100 C  TBL=0 ASSUMES NORMAL ALONG X2
08110     RN(1)=-SIN(TBL)
08120     RN(2)=COS(TBL)
08130     RN(3)=0.
08140 C  FORM INPUT TO STA IN LAB AXES USING REFLECTION FORMULA
08150     T1=RN(1)*TP(ISTR,1)+RN(2)*TP(ISTR,2)+RN(3)*TP(ISTR,3)
08160     DD 10 I=1,3
08170     10 D(I)=TP(ISTR,I)-2.*T1*RN(I)
08180 C  FORM LAB INERTIAL ATTITUDE
08190     CALL LABATT
08200 C  CONVERT TO INERTIAL COORD.
08210     DD 20 I=1,3
08220     C(I)=0.
08230     DD 20 J=1,3
08240     20 C(I)=C(I)+R(J,I,2)*D(J)
08250     RETURN
08260     END
08270 C
08280 C  SUBROUTINE LABATT
08290     COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),XIL(4)
08300     COMMON/5/SSV(27,2),PP(3),B(3,3,2)
08310     BTA=1.-COS(7.27220522E-5*TIME)
08320     R1=0.
08330     R2=0.P29980841
08340     R3=0.557791899
08350     AL=SIN(7.27220522E-5*TIME)
08360     R(1,1,2)=1.-BTA*(R2**2+R3**2)
08370     R(1,2,2)=AL*R3+BTA*R1*R2
08380     R(1,3,2)=-AL*R2+BTA*R1*R3
08390     R(2,1,2)=-AL*R3+BTA*R1*R2
08400

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08410      R(2,2,2)=1.-BTA*(R1**2+R3**2)
08420      R(2,3,2)=AL*R1+BTA*R2*R3
08430      R(3,1,2)=AL*R2+BTA*R1*R3
08440      R(3,2,2)=-AL*K1+BTA*R2*R3
08450      P(3,3,2)=1.-BTA*(R1**2+R2**2)
08460      RETURN
08470      END
08480 C
08490 C
08500      SUBROUTINE GYPCK
08510      COMMON/1/NG,NDELP,NN1
08520      COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
08530      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
08540      DIMENSION TP(3)
08550      PROVIDES ESTIMATED S/C RATES BASED UPON COMPENSATED GYROS.
08560      DO 10 I=1,3
08570      SHIFT PREVIOUS RATE DATA BACK ONE STEP
08580      WR(T,2)=WR(T,1)
08590      COMPUTE NEW GYRO PACKAGE RATE ESTIMATE
08600      TP(I)=-PIMU(I)
08610      DO 10 J=1,NG
08620      TP(T)=TP(I)+IAU(I,J)*WM(J)
08630      10 CONTINUE
08640      L=3
08650      DO 20 I=1,3
08660      WR(T,1)=TP(T)
08670      DO 20 J=1,3
08680      L=L+1
08690      WR(T,1)=WR(T,1)-PIMU(L)*TP(J)
08700      20 CONTINUE
08710      RETURN
08720      END
08730 C
08740 C
08750      SUBROUTINE ATT
08760      PERFORMS NUMERICAL INTEGRATION TO DETERMINE SPACECRAFT ATTITUDE
08770      AS REPRESENTED BY EULER SYMMETRIC PARAMETERS
08780      COMMON/2/TIME,TG,TF,DELT,KDELT,X1(4),X1L(4)
08790      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
08800      DIMENSTION T(5),TP(3)
08810      DO 20 T=1,3
08820      20 TP(I)=.5*(W0(I,1)+WR(I,2))

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09300 C COMPUTE S(0) FOR USE IN RP MATRIX
09310 T(2)=(TP(1)**2+TP(2)**2+TP(3)**2)*DELT**2/4.
09320 T(1) = SQRT(T(2))
09330 T(2) = COS(T(1))
09340 T(3)=.5
09350 IF(ABS(T(1)).LE.1.E-20) GO TO 6
09360 T(3) = SIN(T(1))
09370 T(3)=T(3)/(2.*T(1))
09380 6 CONTINUE
09390 C FORM RP MATRIX FOR PROPAGATING EULER PARAMETERS
09400 RP(1,2)=T(3)*TP(3)*DELT
09410 RP(1,3)=-T(3)*TP(2)*DELT
09420 RP(1,4)=T(3)*TP(1)*DELT
09430 PP(2,3)=PP(1,4)
09440 RP(2,4)=-RP(1,3)
09450 RP(3,4)=RP(1,2)
09460 DO 10 I=1,4
09470 RP(I,I)=-T(2)
09480 DO 10 J=1,I
09490 RP(I,J)=-RP(J,I)
09500 10 CONTINUE
09530 CALL PHT
09550 C PROPAGATE EULER PARAMETERS
09560 DO 12 I=1,4
09570 T(I)=0.
09580 DO 12 J=1,4
09590 T(I)=T(I)+RP(I,J)*XI(J)
09600 12 CONTINUE
09610 C NORMALIZE EULER PARAMETERS
09620 T(5) = SQRT(T(1)**2+T(2)**2+T(3)**2+T(4)**2)
09630 DO 14 I=1,4
09640 XI(I)=T(I)/T(5)
09650 14 CONTINUE
09660 RETURN
09670 END
09680 C
09690 C
09700 SUBROUTINE PHI
09710 C COMPUTES THE STATE TRANSITION MATRICES PHI1 AND PHI2
09720 COMMON/1/NG,NDELP,NN1
09730 COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
09740 COMMON/4/PHT1(4,4),PHI2(4,3),G(7,7),Q(4,6),WR(3,2),RP(4,4)

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09750      DIMENSION W(4),T1(3,12),PK(4,3),PHI2T(4,12),TP1(7,7),TP2(7,7)
09760      DIMENSION P0(7,7)
09770 C      COMPUTE PHI1
09780      DO 10 J=1,4
09790      DO 11 I=1,4
09800      W(I)=0.
09810      DO 11 K=1,4
09820      W(I)=W(I)+RP(I,K)*PHI1(K,J)
09830      11 CONTINUE
09840      DO 10 I=1,4
09850      PHI1(I,J)=W(I)
09860      10 CONTINUE
09880 C      COMPUTE PHI2
09890      DO 42 J=1,4
09900      DO 42 I=1,NN1
09910      PHI2T(I,J)=0.
09920      DO 42 K=1,4
09930      42 PHI2T(I,J)=PHI2T(I,J)+RP(I,K)*PHI2(K,J)
09940      DO 14 I=1,3
09950      PK(I,I)=X1(4)
09960      14 CONTINUE
09970      PK(1,2)=-X1(3)
09980      PK(1,3)=X1(2)
09990      PK(2,3)=-X1(1)
10000      PK(2,1)=X1(3)
10010      PK(3,1)=-X1(2)
10020      PK(3,2)=X1(1)
10030      PK(4,1)=-X1(1)
10040      PK(4,2) = -X1(2)
10050      PK(4,3)=-X1(3)
10060      DO 30 I=1,3
10070      DO 31 J=1,3
10080      31 T1(I,J)=0.
10090      30 T1(I,I)=-1.
10210      JI=1
10220      DO 19 J = 1,3
10250      DO 22 I=1,4
10260      TZ = 0.
10270      DO 23 K=1,3
10280      TZ = TZ+PK(I,K)*T1(K,J)
10290      23 CONTINUE
10300      PHI2(I,J1) = PHI2T(I,J1)+TZ

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10310    22 CONTINUE
10320        J1=J1+1
10330    19 CONTINUE
10350 C      UPDATE Q IF TIME IS APPROPRIATE
10360        KDELT=KDELT+1
10370        IF(KDELT.LT.100) GO TO 50
10380        KDELT=0
10390        DO 55 I=1,4
10400        DO 55 J=1,3
10410        TP2(I,J)=0.
10420        DO 55 K=1,3
10430    55    TP2(I,J)=TP2(I,J)+PK(I,K)*Q0(K,J)
10440        DO 60 I=1,4
10450        DO 60 J=1,4
10460        TP1(I,J)=0.
10470        DO 60 K=1,3
10480    60    TP1(I,J)=TP1(I,J)+TP2(I,K)*PK(J,K)
10490        DO 61 I=5,7
10500        DO 61 J=1,4
10510    61    TP1(I,J)=TP1(J,1)=0.
10520        DO 62 I=5,7
10530        DO 62 J=5,7
10540    62    TP1(I,J)=Q0(I-4,J-1)
10550        T0=RP(2,1)**2+RP(3,1)**2+RP(4,1)**2
10560        T0=SQRT(1.-10000.*T9)
10570        DO 63 I=1,4
10580        DO 64 J=1,4
10590        R0(I,J)=PP(I,J)*100.
10600    64    R0(T+3,J)=0.
10610        DO 65 J=1,3
10620        R0(T,J+4)=-DELT*PK(I,J)*50.
10630    65    R0(T+3,J+4)=0.
10640        R0(I+3,T+3)=1.
10650        R0(I,I)=T9
10660    63    CONTINUE
10670        DO 66 I=1,7
10680        DO 66 J=1,7
10690        TP2(I,J)=0.
10700        DO 66 K=1,7
10710    66    TP2(I,J)=TP2(I,J)+Q(I,K)*RC(J,K)
10720        DO 67 I=1,7
10730        DO 67 J=1,7
```

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10740      Q(I,J)=TP1(I,J)
10750      DO 67 K=1,7
10760      67  Q(T,J)=Q(I,J)+RC(I,K)*TP2(K,J)
10770      50  CONTINUE
10780 C    PHI2 MUST STILL BE MULTIPLIED BY DELT/2 IN PRFIL
10790      RETURN
10800      END
10810 C
10820 C
10830      SUBROUTINE QMAT
10840 C    FORM THE STATE NOISE COVARIANCE MATRIX
10850 C    COMMON/1/NG,NDELP,NN1
10860 C    COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
10870      DIMENSION TP1(7,7)
10880 C    PROPERLY PACK Q MATRIX
10890      DO 10 I=1,7
10900      DO 10 J=1,7
10910      10  TP1(I,J)=Q(I,J)
10920      J3=3
10930      DO 15 I=1,3
10940      J1=3
10950      DO 17 J=1,3
10970      J1=J1+1
10980      Q(I,J1)=Q(J1,I)=TP1(I,J+4)
10990      17  CONTINUE
11010      J3=J3+1
11020      J2=3
11030      DO 16 J=1,3
11050      J2=J2+1
11060      Q(J3,J2)=TP1(I+4,J+4)
11070      16  CONTINUE
11080      15  CONTINUE
11160      RETURN
11170      END
11180 C
11190 C
11200      SUBROUTINE TRAC
11210 C    COMPUTES TRACKER OUTPUT ANGLES FROM ATTITUDE AND
11220 C    TRACKER IDENTIFICATION NUMBER
11230 C    COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
11240 C    COMMON/5/SSV(27,2),PP(3),B(3,3,2)
11250 C    COMMON/6/NTP,ICAT,NO,YL(2,2)

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```
11260 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
11270 DIMENSION T(3),C(3,3),TT(3)
11280 YL(1,1)=Y(1,1)
11290 YL(2,1)=Y(2,1)
11300 CALL TRNS
11400 C COMPUTE TRACKER TRANSFORMATION RELATIVE TO ECI
11410 DO 80 J=1,3
11420 DO 80 J=1,3
11430 C(I,J)=C,
11440 DO 80 K=1,3
11450 C(I,J) =C(I,J)+AST(I,K,NO)*B(K,J,1)
11460 80 CONTINUE
11470 C COMPUTE STAR DIRECTION COSINES IN TRACKER AXES
11480 DO 90 I=1,3
11490 U(I) = C(I,1)*STR(1,1)+C(I,2)*STR(2,1)+C(I,3)*STR(3,1)
11500 90 CONTINUE
11620 U(4)=U(1)/U(2)
11630 U(5)=U(3)/U(2)
11640 U(6)=U(4)*U(5)
11650 U(7)=U(4)**2
11660 U(8)=U(5)**2
11820 C COMPUTE TRACKER OUTPUT IF IT HAD INFINITE BANDWIDTH (INTERVAL AVE.)
11830 Y(1,1)=(-U(4)+ U(6)*SSV(1,NO) +U(5)*SSV(2,NO)
11840 1-(1.+U(7))*SSV(3,NO))
11850 Y(2,1)=(U(5) -(1.+U(8))*SSV(1,NO) )+U(4)*SSV(2,NO)
11860 1+U(6)*SSV(3,NO)
11870 C INCLUDE TRACKER DYNAMIC EFFECTS (HI BW TRACKER)
11880 Y(1,1) =Y(1,1 )-SSV( 22 ,NO) *7.272205E-5
11890 100 RETURN
11900 END
11910 C
11920 C
11930 SUBROUTINE TRCFLT
11940 COMMON/2/TTME,TO,TF,DELT,KDELT,X1(4),X1L(4)
11950 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
11960 COMMON/6/NTR,ICAT,NO,YL(2,2)
11970 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
11980 DIMENSION C(2),R(2)
11990 C PRINTS FILTERED TRACKER OUTPUT
12000 C(1)=SSV(26,NO)/DELT
12010 C(2)=SSV(27,NO)/DELT
12020 R(1)=EXP(-1./C(1))
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12030      R(2)=EXP(-1./C(2))
12040      DO 10 K=1,2
12050      DO 10 T=1,2
12060 10   YD(I,K)=YD(T,K)*R(I)+(1.-C(I))*(1.-R(I))*Y(I,K)
12070      1+(C(I)*(1.-R(I))-R(I))*YL(I,K)
12080      RETURN
12090      END
12100 C
12110 C
12120      SUBROUTINE PRFIL
12130      CONVERTS 4-PARAMETER ATTITUDE SYSTEM TO 3 PARAMETERS AND MODIFIES
12140      STATE TRANSITION MATRIX
12150      COMMON/1/NG,NDELP,NN1
12160      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
12170      COMMON/3/PTM(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
12180      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),QD(4,6),WR(3,2),RP(4,4)
12190      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
12200      COMMON/6/NTR,ICAT,NO,YL(2,2)
12210      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
12220      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
12230      DIMENSION W(3)
12240      W(1)=X1L(1)/X1L(4)
12250      W(2)=X1L(2)/X1L(4)
12260      W(3)=X1L(3)/X1L(4)
12270      DO 10 I=1,3
12280      DO 10 J=1,3
12290      PHI1(I,J)=PHI1(I,J)-PHI1(I,4)*W(J)
12300 10    CONTINUE
12310      DO 12 I=1,3
12320      DO 12 J=1,NN1
12330      PHI2(I,J)=PHI2(I,J)*DELT/2.
12340 12    CONTINUE
12350      RETURN
12360      END
12370 C
12380 C
12390      SUBROUTINE HMTRX
12400      COMPUTES MEASUREMENT MATRIX
12410      COMMON/1/NG,NDELP,NN1
12420      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
12430      COMMON/6/NTR,ICAT,NO,YL(2,2)
12440      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)

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12450 COMMON/P/P(7,7),R(2,2),AK(6,2),HMAT(2,7)
12460 DIMENSION T(3),T1(4,4),T1(3,4)
12470 DIMENSION TA(2,4)
12780 DO 130 T=1,4
12790     TT(T,T)=0.
12800 130 CONTINUE
12810     TT(1,2) = -STR(3,1)
12820     TT(1,3) = STR(2,1)
12830     TT(1,4) = STR(1,1)
12840     TT(2,3) = -STR(1,1)
12850     TT(2,4) = STR(2,1)
12860     TT(3,4) = STR(3,1)
12870     TT(2,1) = -TT(1,2)
12880     TT(3,1) = -TT(1,3)
12890     TT(3,2) = -TT(2,3)
12900     TT(4,1) = TT(1,4)
12910     TT(4,2) = TT(2,4)
12920     TT(4,3) = TT(3,4)
12930     T(1) = -X1(1)/X1(4)
12940     T(2) = -X1(2)/X1(4)
12950     T(3) = -X1(3)/X1(4)
12960     DO 160 T=1,3
12970     DO 160 J=1,3
12980     TT(I,J) = TT(I,J)+STR(I,1)*T(J)
12990 160 CONTINUE
13000     DO 165 I=1,3
13010     T1(I,1) = (-AST(I,1,NO)*X1(4)+AST(I,2,NO)*X1(3)
13020     1-AST(I,3,NO)*X1(2))*2.
13030     T1(I,2) = (-AST(I,1,NO)*X1(3)-AST(I,2,NO)*X1(4)
13040     1+AST(I,3,NO)*X1(1))*2.
13050     T1(I,3) = (AST(I,1,NO)*X1(2)-AST(I,2,NO)*X1(1)
13060     1-AST(I,3,NO)*X1(4))*2.
13070     T1(I,4) = (-AST(I,1,NO)*X1(1)-AST(I,2,NO)*X1(2)
13080     1-AST(I,3,NO)*X1(3))*2.
13090 165 CONTINUE
13100     DO 166 K=1,4
13110     TA(1,K)=T1(1,K)/U(2)-T1(2,K)*U(1)/U(2)**2
13120     TA(2,K)=T1(2,K)*U(3)/U(2)**2-T1(3,K)/U(2)
13130 166 CONTINUE
13140     DO 170 J=1,3
13150     HMAT(1,J)=0.
13160     HMAT(2,J)=0.
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13170 DD 180 K=1,4
13180   HMAT(1,J)=HMAT(1,J)+TA(1,K)*TT(K,J)
13190   HMAT(2,J)=HMAT(2,J)+TA(2,K)*TT(K,J)
13200 180 CONTINUE
13210   RETURN
13220   END
13230 C
13240 C
13250 SUBROUTINE RMAT
13260 C FORMS MEASUREMENT NOISE COVARIANCE MATRIX
13270 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
13280 COMMON/F/NTR,LCAT,NO,YL(2,2)
13290 COMMON/P/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
13300 P(1,2)=P(2,1)=0.
13310 R(1,1)=SSV(24,NC)**2
13320 R(2,2)=SSV(25,NC)**2
13330 RETURN
13340 END
13350 C
13360 C
13370 SUBROUTINE FILT
13380 C USING KALMAN FILTER EQUATIONS, COMPUTES FILTER GAINS, AK, AND PROPAGATES
13390 C ERROR COVARIANCE MATRIX,P
13400 COMMON/1/NG,NDELP,NN1
13410 COMMON/3/PTMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
13420 COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
13430 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
13440 COMMON/P/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
13450 DIMENSION TA(7,7),TB(7)
13460 C COMPUTE ADDITIONAL CONSTANTS FOR PARTITIONING MATRICES
13465 NN2=NN1
13470 NN3=NN1-NN2
13480 N=NN1+3
13490 M=?
13500 CALL SRMMUL(PHI1,1,1,3,3,P,1,1,3,TA,1,1,4,7,7)
13510 CALL SRMMUL(PHI2,1,1,3,NN2,P,4,1,3,P,1,1,4,7,7)
13520 CALL SRMADD(TA,1,1,P,1,1,1A,1,1,3,3,7,7,7)
13530 CALL SRMMUL(PHI1,1,1,3,3,P,1,4,NN2,TA,1,4,4,7,7)
13540 CALL SRMMUL(PHI2,1,1,3,NN2,P,4,4,NN2,P,1,4,4,7,7)
13550 CALL SRMADD(TA,1,4,P,1,4,P,1,4,3,NN2,7,7,7)
13560 CALL SRMMUL(PHI1,1,1,3,3,P,1,4+NN2,NN3,TA,1,4+NN2,4,7,7)
13570 CALL SRMMUL(PHI2,1,1,3,NN2,P,4,4+NN2,NN3,P,1,4+NN2,4,7,7)

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13580      I1=4+NM2
13590      CALL SRMADD(TA,1,I1,P,1,I1,P,1,I1,3,NN3,7,7,7)
13600      DD 15 T=1,3
13610      DD 15 K=1,3
13620      P(I,K)=0.
13630      DD 15 J=1,3
13640      15 P(I,K)=P(T,K)+TA(1,J)*PHI1(K,J)
13650      DD 20 T=1,3
13660      DD 20 K=1,3
13670      TA(T,K)=0.
13680      DD 20 J=1,NN2
13690      20 TA(I,K)=TA(T,K)+P(I,J+3)*PHI2(K,J)
13700      CALL SRMADD(P,1,1,TA,1,1,P,1,1,3,3,7,7,7)
13710      CALL SRMTRA(P,1,4,3,NN2,P,4,1,7,7)
13720      CALL SRMTRA(P,1,4+NN2,3,NN3,P,4+NN2,1,7,7)
13730 C     P=PHT P PHI-TRANSPOSE HAS BEEN COMPUTED
13740      CALL SRMADD(P,1,1,Q,1,1,P,1,1,N,N,7,7,7)
13750      RETURN
13760      ENTRY FFILT
13770      CALL SPMMUL(HMAT,1,1,M,N,P,1,1,N,TA,1,1,2,7,7)
13780      CALL SPMTBA(HMAT,1,1,M,N,AK,1,1,2,8)
13790      CALL SPMMUL(TA,1,1,M,N,AK,1,1,M,TA,M+1,1,7,8,7)
13800      CALL SRMADD(TA,M+1,1,R,1,1,TA,1,1,M,M,7,2,7)
13810 C     INVERSE ROUTINE FOLLOWS
13820      DET=TA(1,1)*TA(2,2)-TA(2,1)*TA(1,2)
13830      TA(1,M+1)=TA(2,2)/DET
13840      TA(1,M+2)=-TA(1,2)/DET
13850      TA(2,M+1)=-TA(2,1)/DET
13860      TA(2,M+2)=TA(1,1)/DET
13870 C     END OF TNVERSE ROUTINE
13880      CALL SPMMUL(AK,1,1,N,M,TA,1,M+1,M,TA,1,1,8,7,7)
13890      CALL SPMMUL(P,1,1,N,N,TA,1,1,M,AK,1,1,7,7,8)
13900 C     AK HAS BEEN COMPUTED
13910      DD 45 T=1,M
13920      DD 45 K=1,N
13930      TA(T,K)=0.
13940      DD 40 J=1,M
13950      40 TA(T,K) = TA(I,K)-AK(I,J)*HMAT(J,K)
13960      TF (I,NE,K) GO TO 40
13970      TA(T,K) = 1.+TA(I,K)
13980      45 CONTINUE
13990      DD 55 I=1,N

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14000      D7 50 K=1,N
14010      TR(K)=0.
14020      D0 50 J=1,N
14030      S0 TP(K)=TR(K)+TA(I,J)*P(J,K)
14040      D7 55 K=1,N
14050      S5 TA(I,K)=TB(K)
14060 C     SYMMETRIZE ERROR COVARIANCE MATRIX
14070      D0 60 I=1,M
14080      D0 60 J=1,N
14090      60 P(I,J)=0.5*(TA(I,J)+TA(J,I))
14100 C     P(K+1) HAS BEEN COMPUTED
14110      RETURN
14120      END
14130 C
14140 C
14150      SUBROUTINE SRMMUL(A,IMA,INA,MA,NA,B,IMB,INB,NB,C,IMC,INC,IRA,IRB,
14160      1IRC)
14170 C     C=A+B WITH INIT. ARRAY ELEMENTS SPECIFIED
14180      DIMENSION A(49),B(49),C(49)
14190      D0 5 J=1,MA
14200      IPIMC = I+IMC
14210      IPIMA = I+IMA
14220      IF (NR.LT.1) GO TO 6
14230      D0 5 K=1,NB
14240      KPINC = K+INC
14250      KPINB = K+INB
14260      IC = IPIMC-1+(KPINC-2)*IRC
14270      C(IC) = 0.
14280      IF (NA.LT.1) GO TO 6
14290      D0 5 J=1,NA
14300      JPINA = J+INA
14310      JPIMB = J+IMB
14320      IA = IPIMA-1+(JPINA-2)*IRA
14330      IP = JPIMB-1+(KPINB-2)*IRB
14340      5 C(IC) = C(IC)+A(IA)*B(IB)
14350      6 RETURN
14360      END
14370 C
14380 C
14390      SUBROUTINE SRNALD(A,IMA,INA,B,IMB,INB,C,IMC,INC,M,N,IRA,IRE,1RC)
14400 C     C=A+B WITH INIT. ARRAY ELEMENTS SPECIFIED
14410      DIMENSION A(49),B(49),C(49)

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14420      D7 5 I=1,M
14430      TF (N,LT,1) GO TO 6
14440      DD 5 J=1,N
14450      TPIMC = I+TMC
14460      JPINC = J+INC
14470      IPTMA = I+IMA
14480      JPINA = J+INA
14490      TPIMR = I+TMR
14500      JPINR = J+TNR
14510      IA = IPTMA-1+(JPINA-2)*IRA
14520      IR = TPIMR-1+(JPINB-2)*IRB
14530      IC = IPTMC-1+(JPINC-2)*IRC
14540      5 C(IC) = A(IA)+B(IB)
14550      6 RETURN
14560      END
14570 C
14580 C
14590      SUBROUTINE SRMTRA(A,IMA,INA,M,N,B,IMB,INB,IRA,IRB)
14600      DIMENSION A(49),B(49)
14610 C      B=A-TRANSPOSE WITH INIT. ARRAY ELEMENTS SPECIFIED
14620      IF (N.LT.1) GO TO 6
14630      DD 5 I=1,N
14640      DD 5 J=1,M
14650      TPIMR = I+TMR
14660      JPINR = J+INB
14670      JPIMA = J+IMA
14680      TPINA = I+INA
14690      TA = J*TPIMA-1+(JPINA-2)*IRA
14700      TR = TPIMR-1+(JPINB-2)*IRB
14710      5 B(IR)=A(TA)
14720      6 RETURN
14730      END
14740 C
14750 C
14760      SUBROUTINE PGFIL
14770 C      UPDATES ATTITUDE VARIABLES AND OTHER SYSTEM ELEMENTS OF THE
14780 C      STATE VECTOR
14790 C      COMMON/1/NG,NDELP,NV1
14800 C      COMMON/2/TTYPE,IC,TF,DELT,KDELT,X1(4),X1L(4)
14810 C      COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
14820 C      COMMON/5/SSV(27,2),PP(3),R(3,3,2)
14830 C      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)

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14840      COMMON/R/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
14850      DIMENSION W(3),T(3)
14860      W(1)=YD(1,2)-YD(1,1)
14870      W(2)=YD(2,2)-YD(2,1)
14900 C    COMPUTE CORRECTION FOR EACH SYSTEM PARAMETER OF STATE VECTOR
14910      DO 17 I=1,MMI
14920      W(3) = AK(I+3,1)*W(1)+AK(I+3,2)*W(2)
15020      PIMU(I)=PIMU(I)+W(3)
15060      11 CONTINUE
15080 C    COMPUTE CORRECTIONS FOR EACH ATTITUDE VARIABLE
15090      DO 9 I=1,3
15100      T(I) = AK(I,1)*W(1)+AK(I,2)*W(2)
15110      9 CONTINUE
15120 C    UPDATE ATTITUDE VARIABLES
15130      X1(4)=X1(4)-(X1(1)*T(1)+X1(2)*T(2)+X1(3)*T(3))/X1(4)
15140      DO 10 I=1,3
15150      X1(I)=X1(I)+T(I)
15160      10 CONTINUE
15170      RETURN
15180      END
15190 C
15200 C
```

APPENDIX B

**DATA ANALYSIS PROGRAM LISTING FOR THE
GIMBAL SYSTEM TEST**

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00100      PROGRAM PADS(INPUT,OUTPUT,TAPE1,TAPE2,TAPE4,TAPE5)
00110      COMMON/1/NG,NDELP,NN1
00120      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4),KSKP
00130      COMMON/3/PTM(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
00140      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
00150      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
00160      COMMON/6/NTR,ICAT,NO,YL(2,2)
00170      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
00180      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
00190      DIMENSION GYDAT(500,14),GX1(14),GX2(14),MSTR(20)
00192 C      KTYP=0 - PEAL LAB ;KTYP=1 - GYROS REORIENTED;
00194 C      KTYP=2 - IDFAL GYROS
00200      DATA KTYP/0/
00203 C      MSTR(I) DENOTES WHETHER THE I TH VISIBLE STAR WILL BE USED
00204 C      FOR FILTERING; IF SO, MSTR(I)=1
00205      DATA (MSTR(I),I=1,17)/1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1/
00206      5 FORMAT(X,7HKTYP = ,II/)
00210      1 CONTINUE
00212      N7=3
00220 C      REWIND TAPES
00230      REWIND 1
00240      REWIND 2
00250      REWIND 4
00255      REWIND 5
00260      WRTTE(2,5) KTYP
00260 C      EFFECTIVELY ELIMINATE THE FIRST DATA LINE
00280      READ(4,2) (GYDAT(1,J),J=1,14)
00310      NN1=3
00320 C      READ IN AND PRINT OUT INITIAL VALUES, SYSTEM PARAMETERS AND RUN
00330 C      CONTROL CONSTANTS
00340      CALL INPUT
00350 C      INITIATE COUNTERS AND FLAGS
00360      NXC=KPP=NF=0
00370      IGY=500
00375      MT=KKF=0
00380      NO=1
00390      READ(4,2) (GX1(J),J=1,14)
00400 C      BEGINNING OF FILTER LOOP
00410 C      INITIATE STATE TRANSITION MATRICES PHI1 AND PHI2
00420      15 CONTINUE
00440      CALL ZFPN
00460      20 CONTINUE

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00490 C INDEX, THEN TEST FOR WHETHER NEW FLIGHT GYRO DATA SHOULD BE READ
00500 TGY=TCY+1
00510 IF(TCY.LE.500) GO TO 23
00520 TGY=1
00530 DO 24 T=1,500
00540 RFAD(4,2) (GX2(J),J=1,14)
00550 DLT=GX2(1)-GX1(1)
00560 GYDAT(I,1)=GX1(I)
00570 DO 17 K=2,4
00580 17 GYDAT(T,K)=(GX2(K)-GX1(K))/DLT*4.8481368E-6
00590 IF(KTYP.EQ.C) GO TO 25
00592 IF(KTYP.EQ.1) GO TO 26
00600 GYDAT(T,2)=-4.66164026E-5
00610 GYDAT(T,3)=-4.49498700E-5
00620 GYDAT(T,4)=4.57512760E-5
00622 GO TO 25
00623 26 CONTINUE
00624 GYDAT(I,2)=GYDAT(I,2)+4.26794875E-5
00625 GYDAT(I,3)=GYDAT(I,3)+2.11571588E-6
00626 GYDAT(I,4)=GYDAT(I,4)+1.97941384E-5
00630 25 CONTINUE
00640 DO 18 K=5,14
00650 18 GYDAT(I,K)=GX1(K)
00660 DO 19 K=1,14
00670 19 GX1(K)=GX2(K)
00680 IF(E0F,4) 23,24
00690 24 CONTINUE
00700 C FORMAT 2 IS BELSKYS TAPE FORMAT
00710 2 FORMAT(X,F10.3,3(F12.1),F3,X,F11.1,X,2(F7.1,X),2(F11.1,X),
00711 14(F5.1,X))
00720 C FORM TIME AND INTEGRATION STEP
00730 23 CONTINUE
00740 DELT=GYDAT(TGY,1)-TIME
00750 TTME=GYDAT(TGY,1)
00760 DO 33 I=1,NC
00770 33 WM(I)=GYDAT(1GY,I+1)
00890 C TEST FOR END OF RUN
00900 TF(TTME.LT.TF) GO TO 43
00910 STOP
00920 43 CONTINUE
00930 C ADVANCE STATE PRINT COUNTER
00940 NXC=NXC+1

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00950 C COMPUTE ESTIMATED SPACECRAFT BODY ANGULAR RATES
00960 CALL GYPCK
00970 C COMPUTE ESTIMATED SPACECRAFT ATTITUDE
00980 CALL ATT
00990 C TTME TO PRINT STATE
01000 IF(NXC.LT.NDelp) 44,81
01010 81 CONTINUE
01020 C FORM ESTIMATED SPACECRAFT ATTITUDE DIRECTION COSINE MATRIX
01030 CALL TPDNS
01060 C PRINT ESTIMATED STATE
01070 CALL X1PRNT
01140 NXC=0
01150 C IF KPP=1, THIS PRINT FOLLOWED A FILTER OPERATION
01160 IF(KPP.F0.1) 46,44
01170 48 KPP=0
01180 GO TO 15
01190 44 CONTINUE
01230 C TEST IF TRACKER DATA IS PRESENT
01240 IF(GYDAT(IGY,5).GT.0.5) 60,52
01250 52 NF=-KSKP
01255 KKF=0
01260 GO TO 20
01300 60 CONTINUE
01305 IF(KKF.F0.1) GO TO 20
01310 IF(GYDAT(IGY,5).GT.1.5) GO TO 601
01312 MT=MT+1
01320 DV1=GYDAT(IGY,13)
01330 DV2=GYDAT(IGY,14)
01340 601 CONTINUE
01350 NF=NF+1
01360 IF(NF.LT.1) GO TO 20
01362 C TEST WHETHER THIS STAR IS ACCEPTABLE
01364 IF(MSTR(MT).NE.1) GO TO 52
01370 TU=GYDAT(TGY,7)+DV2
01380 TV=GYDAT(TGY,8)+DV1
01450 YL(1,2)=Y(1,2)
01460 YL(2,2)=Y(2,2)
01470 Y(1,2) =- TU*4.84613681E-6
01480 Y(2,2) = TV*4.84613681E-6
01482 YG= GYDAT(TGY,6)*4.64613681E-6
01490 C AIR REFRACTION TABLE ANGLE COMPUTATION
01520 TRL= GYDAT(TGY,9)*4.34613681E-6

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01530 IF(NF.EQ.1) 62,61
01540 62 CALL STRCHK(YG)
01550 61 CONTINUE
01560 C COMPUTE INERTIAL STAR DIR. COS.
01570 CALL STARDC(STR(1,1),ICAT,TBL)
01580 C COMPUTE EST. TRACKER OUTPUT
01590 CALL TRAC(YG)
01600 CALL TPFELT
01610 IF(NF.LT.10) GO TO 20
01615 KKF=1
01620 C START FILTERING
01630 C COMPUTE TRACKER MEASUREMENT RESIDUAL NORM
01640 W1=SQRT((YD(1,2)-YD(1,1))**2+(YD(2,2)-YD(2,1))**2)
01650 C DOES IT FALL WITHIN AN ALLOWABLE ERROR
01660 IF(W1.LT..1) GO TO 70
01670 72 PRINT 3,W1
01680 3 FORMAT(20HMEASUREMENT ERROR IS,2X,E13.6,6H, PUNT)
01690 STOP
01700 70 CONTINUE
01701 X09=0.
01705 WRITE(5,4) TIME,W1,X09,N7
01706 4 FORMAT(3(2X,E13.6),2X,I11)
01710 CALL XIPRNT
01720 NF=-KSKP
01730 C FORM STATE NOISE ERROR COVARIANCE MATRIX
01740 CALL QMAT
01750 C ALTER STATE TRANSITION MATRIX TO DEAL WITH 3 RATHER THAN 4
01760 C ATTTTF VAPIABLES
01770 CALL PRFIL
01780 C PROPAGATE STATE ERROR COVARIANCE MATRIX
01790 CALL FILT
01795 CALL PRNT(1)
01800 C FORM MEASURMENT MATRIX
01810 CALL HMTRX
01820 C FORM MEASUREMENT NOISE COVARIANCE MATRIX
01830 CALL RMAT
01840 C APPLY KALMAN ALGORITHM
01850 CALL FFILT
01860 C UPDATE STATE
01870 CALL PRFIL
01880 C ADVANCE FILTER COUNTER
01890 MPC=MPC+1

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01900 C      TIME TO PRINT STATE ERROR COVARIANCE MATRIX
01910      IF(NPC-NFP) 15,80,80
01920      80  CONTINUE
01930      CALL PRNT(1)
01940      KPR=1
01950      GO TO 81
01960      END
01970 C
01980 C
01990      SUBROUTINE TRNS
02000 C      COMPUTE DIRECTION COSINES OF SPACECRAFT ATTITUDE RELATIVE TO
02010 C      ATTITUDE REFERENCE AXES(ECI COORDINATES)
02020      COMMON/2/TIME,T0,TFDELT,KDELT,X1(4),X1L(4)
02030      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
02040      DIMENSION T(4,4)
02050 C      TRANSFORM FULL SYMMETRIC PARAMETERS TO DIRECTION COSINES RELATIVE
02060 C      TO ECI AXES
02070      DO 10 I = 1,3
02080      T(I,I) = X1(4)
02090      10 CONTINUE
02100      T(1,2)=X1(3)
02110      T(1,3)=-X1(2)
02120      T(1,4)=X1(1)
02130      T(2,3)=X1(1)
02140      T(2,4)=X1(2)
02150      T(3,4)=X1(3)
02160      T(2,1) = -T(1,2)
02170      T(3,1) = -T(1,3)
02180      T(3,2) = -T(2,3)
02190      T(4,1) = T(1,4)
02200      T(4,2) = T(2,4)
02210      T(4,3) = T(3,4)
02220      T(4,4) = -X1(4)
02230      DO 40 I=1,3
02240      DO 40 J=1,3
02250      B(I,J,1)=0.
02260      DO 40 K=1,4
02270      B(I,J,1)= - B(I,J,1)+T(I,K)*T(K,J)
02280      40 CONTINUE
02290      RETURN
02300      END
02310 C

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02320 C
03100      SUBROUTINE XIPRNT
03110 C      PRINTS ESTIMATED STATE VECTOR AND S/C ATTITUDE MATRIX
03120      COMMON/1/NG,NDELP,NN1
03130      COMMON/2/TIME,T0,TF,DELT,KDELT,X1(4),X1L(4)
03140      COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
03150      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
03160      DTMENSTN C(3,3),D(4)
03170      CA=206264.81
03175      N7=1
03180 C      PRINT HEADING AND TIME
03190      WRITE(2,30) TIME
03200      CALL LABATT
03210      DO 60 I=1,3
03220      DO 60 J=1,3
03230      C(I,J)=0.
03240      DO 60 K=1,3
03250      60 C(I,J)=C(I,J)+B(I,K,1)*B(J,K,2)
03260      D(1)=CA*C(2,3)
03270      D(2)=CA*C(3,1)
03280      D(3)=CA*C(1,2)
03290      D(4)=SQRT(D(2)**2+D(3)**2)
03291      DISPLAY TIME,D(4),D(1)
03300 C      PRINT ESTIMATED EULER PARAMETERS AND S/C AND LAB ATTITUDE MATRIX
03310      WRITE(2,20) (I,X1(I),B(I,1,1),B(I,2,1),B(I,3,1),
03320      1B(I,1,2),B(I,2,2),B(I,3,2),D(I),I=1,3)
03330      WRITE(2,22) X1(4),D(4)
03340      WRITE(5,23) TIME,D(4),D(1),N7
03350      23 FORMAT(3(2X,E13.6),2X,11)
03390 C      PRINT HEADING
03400      WRITE(2,50)
03420      DO 45 T=1,NN1
03520      PTMU1A=CA*PTMU(I)
03530      WRITE(2,21) I,PTMU1A
03570      45 CONTINUE
03590      30 FORMAT(X///RH TIME = ,E16.9//30X,
03600      150HESTIMATED SPACECRAFT ATTITUDE RELATIVE TO ECI AXES//X,
03610      23HNO.,X,114HULEF PARAM,12X,17HATTITUDE ESTIMATE,27X,
03620      31?HLAB ATTITUDE,12X,12HR,P,Y,RSS ER//)
03630      20 FORMAT(X,T1,2X,F12.9,X,3(X,F12.9),2X,3(X,F12.9),2X,F9.2)
03640      22 FORMAT(X,1H4,2X,F12.9,B3X,F9.2)
03650      50 FORMAT(X/14X,26HESTIMATED GYRO BIAS VECTOR//)

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03660 21 FORMAT(15Y,I1,4X,E12.5)
03670      RETURN
03680      FND
03690 C
03700 C
03710      SUBROUTINE PRNT(K1)
03720      COMMON/1/NG,NDELP,NN1
03730      COMMON/2/TIME,FG,TF,DELT,KDELT,X1(4),XIL(4)
03740      COMMON/6/NTP,1CAT,NO,YL(2,2)
03750      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
03760      COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
03770      DIMENSION PT(3,3),F(3,3),TP(3,3)
03775      N7=2
03780 C      PRINTS THE ERROR COVARIANCE MATRIX, UPPER LEFT 3 BY 3 IN
03790 C      SMALL ANGLE FORM
03800 C      SAVE UPPER 3 BY 3
03810      DO 40 I=1,3
03820      DO 40 J=1,3
03830 40  PT(I,J)=P(I,J)
03840 C      CONVEPT UPPER 3 BY 3 OF P MATRIX TO SMALL ANGLE FORM
03850      F(1,1)=2.*((X1(4) +X1(1)**2/X1(4))
03860      F(1,2)=2.*((X1(3)+X1(1)*X1(2))/X1(4))
03870      F(1,3)=-2.*((X1(2)-X1(1)*X1(3))/X1(4))
03880      F(2,1)=-2.*((X1(3)-X1(2)*X1(1))/X1(4))
03890      F(2,2)=2.*((X1(4) +X1(2)**2/X1(4))
03900      F(2,3)=2.*((X1(1)+X1(2)*X1(3))/X1(4))
03910      F(3,1)=2.*((X1(2)+X1(1)*X1(3))/X1(4))
03920      F(3,2)=-2.*((X1(1)-X1(2)*X1(3))/X1(4))
03930      F(3,3)=2.*((X1(4) +X1(3)**2/X1(4))
03940      DO 70 I=1,3
03950      DO 70 J=1,3
03960      TP(I,J)=0.
03970      DO 70 K=1,3
03980 70  TP(I,J)=TP(I,J)+F(I,K)*F(J,K)
03990      DO 75 I=1,3
04000      DO 75 J=1,3
04010      P(I,J)=0.
04020      DO 75 K=1,3
04030 75  P(I,J)=P(I,J)+F(I,K)*TP(K,J)
04070      NA = NN1+3
04100 C      PRNTNT HEADING
04110 10  WRITTE(2,1)

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04120 1 FORMAT(1H1,5UX,0HP MATRIX)
04130  DD 20 I=1,NA
04140  WRITE(2,3) T
04150  3 FORMAT(/PX,4HROW ,I2/)
04160 C PRINT P MATRIX
04170 20 WRITE(2,30) (P(I,J),J=1,NA)
04180 30 FORMAT(3X,6F17.6)
04190  TF(K1,F0.0) GO TO 44
04200 C PRINT STAR NUMBER
04210 50 WRITE(2,45) ICAT
04220 45 FORMAT( / 7X,14HSTAR NUMBER = ,I3)
04230  TST1=YD(2,2)
04240  TST2=YD(1,2)
04250  DEL1=(TST1-YD(2,1))*206264.81
04260  DEL2=(TST2-YD(1,1))*206264.81
04280  WRITE(2,60) TST1,DEL1,TST2,DEL2
04290 60 FORMAT(3X,37HTRACKER OUTPUT ANGLES AND MEAS. ERROR/
04300 15X,7HAZIMUTH,2X,E11.4,5H RAD.,3X,F10.3,
04310 27H APCSEC/6X,5HELEV ,3X,E11.4,5H RAD.,3X,F10.3,
04320 37H ARCSFC)
04330 44 CONTINUE
04340  AT=SQRT(P(2,2) +P(3,3))*206264.81
04350  WRITE(2,39) AT
04360 39 FORMAT(26H SQRT OF POINTING TRACE = ,F10.3,9H ARC SEC.)
04361  AT1=SQRT(P(1,1))*206264.81
04362  WRITE(2,391) AT1
04363 391 FORMAT(X,17HBORESIGHT ERROR = ,F10.3,9H ARC SEC.)
04365  WRITE(5,8) TIME,AT,AT1,N7
04366 8 FORMAT(3(2X,E13.6),2X,I1)
04370  DISPLAY AT,AT1
04380 C RESTORE P MATRIX
04390  DD 43 I=1,3
04400  DD 43 J=1,3
04410 43 P(I,J)=PT(I,J)
04420  RETURN
04430  END
04440 C
04450 C
04460  SURROUNTING INPUT
04470 C READS IN AND PRINTS INITIAL VALUES, SYSTEM PARAMETERS, RUN CONTROL
04480 C CONSTANTS, AND CONVERTS SPECIFIED ANGLES TO RADIANS
04490 C COMMON/I/NC,NDELP,NN1

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04970      COMMON/2/TIME,TG,TF,DELT,KDELT,X1(4),X1L(4),RSKP
04980      COMMON/3/PTM,U(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
04990      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),QO(4,6),WR(3,2),RP(4,4)
05000      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
05010      COMMON/6/NTP,ICAT,NO,YL(2,2)
05020      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
05030      COMMON/P/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
05040      DIMENSION NSV(4,32),C(3,3),T(3)
05050      NN=NN+3
05060      DD 112 I=1,MN
05070      DC 112 J=1,NN
05080  112  P(I,J)=0(I,J)=0.
05090 C      READ INPUT FLAGS DEFINING TYPE OF RUN AND PRINT OPTIONS
05100      READ(1,2) NTR,NG
05110  2     FORMAT(1I)
05120      READ(1,3) NDELP,RSKP
05130  3     FORMAT(1I)
05150 C      READ NOMINAL STAR TRACKER TRANSFURMATION MATRIX
05160      DD 20 K=1,NTR
05170  20    PFAD(1,4) ((AST(1,J,K),J=1,3),I=1,3)
05180  4     FORMAT(F9.6)
05200 C      READ STAR SENSOR PARAMETERS
05210      DD 24 J=1,NTR
05230  24    PFAD(1,5) (SSV(I,J),I=1,9)
05240  5     FORMAT(F9.3)
05250 C      READ GYPC PARAMETERS
05260      DD 25 J=1,NG
05270  25    READ(1,6) (GY(I,J),I=1,9)
05280 C      READ ESTIMATED INITIAL RATES
05300      DD 27 I=1,3
05310  27    READ(1,6) PP(I)
05330  6     FORMAT(F12.6)
05340 C      READ INITIAL 4 PARAMETER ATTITUDE
05350      READ(1,4) (X1(I),I=1,4)
05360  22    CONTINUE
05370 C      READ TOTAL AND FINAL TIMES AND INTEGRATION STEP SIZE
05380      READ(1,6) TO,TF,DELT
05390 C      READ ERROR COVARIANCE INITIAL DIAGONAL ELEMENTS
05400 C      UNITS ARE RAD.,SEC
05410      DD 28 I=1,NN
05420  28    READ(1,6) P(I,I)
05470 C

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05490 C      TEMPORARY INPUT PRINT ROUTINE
05500      WRITE(2,12)
05510      12 FORMAT(1H1)
05520      WRITE(2,7) NTR,NG,NDELP
05540      7 FORMAT( 3(X,I3)/)
05560      DD 31 J=1,NG
05570      31 WRITE(2,8) (GY(I,J),I=1,9)
05580      8 FORMAT(0(X,F10.3))
05590      WRITE(2,10)
05600      10 FORMAT(/)
05610      DO 32 K=1,NTR
05620      32 WRITE(2,9)((AST(I,J,K),J=1,3),I=1,3)
05630      9 FORMAT(0(X,E9.6))
05640      WRITE(2,10)
05650      DO 34 J=1,NTR
05670      34 WRITE(2,11) (SSY(I,J),J=1,9)
05680      11 FORMAT(9(X,F10.3))
05690      WRITE(2,10)
05700      DO 35 J=1,3
05720      35 WRITE(2,9) PP(J)
05730      41 CONTINUE
05740      WRITE(2,10)
05760      WRITE(2,8) (X1(I),I=1,4)
05770      WRITE(2,10)
05780      DO 37 K=1,NN
05790      37 WRITE(2,8) P(K,K)
05800      WRITE(2,10)
05810      WRITE(2,9) T0,TF,DELT
05820      WRITE(2,10)
05880 C
05890 C      INITIALIZE PROBLEM TIME
05900      TIME = T0
05910      15 FORMAT(1H1)
05920      WRITE(2,15)
05930 C      CONVERT ANGLES TO RADIANS
05940      CF = 4.8481368E-06
05950      CFQ = CF*CF
05970      DO 39 J=1,NTR
05980      39 DD 131 I=1,7
05990      131 SSV(I,J)=CF*SSV(I,J)
06000      130 CONTINUE
06020      DD 135 J=1,NG

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06030      GY(I,J)=GY(I,J)*CF
06040      DO 135 I=7,9
06050      GY(I,J)=GY(I,J)*CF
06060 135 CONTINUE
06070      CALL TNINITIAL
06080 C     PRTNT ERROR COVARIANCE MATRIX
06090      CALL PPNT(0)
06100 C     PPTNT INITIAL STATE VECTOR
06110      CALL TRNS
06130      CALL X1PPNT
06160      RETURN
06190      END
06200 C
06210 C
06220      SUBROUTINE ZERO
06230 C     INITIALIZES STATE TRANSITION MATRICES PHI1 AND PHI2 AFTER EACH
06240 C     FILTER UPDATE
06250      COMMON/1/NG,NDELP,NN1
06260      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
06270      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),QQ(4,6),WR(3,2),RP(4,4)
06280 C     RETAIN FILTER UPDATED VALUES OF EULER PARAMETERS FOR NEXT FILTER
06290 C     OPERATION
06300      DO 21 I=1,4
06310      X1L(I)=X1(I)
06320 C     SET PHT1 ELEMENTS EQUAL TO ZERO
06330      DO 22 J=1,4
06340      PHI1(T,J)=0.
06350 22 CONTINUE
06360 C     SET PHI2 ELEMENTS EQUAL TO ZERO
06370      DO 23 J=1,NN1
06380      PHI2(I,J)=0.
06390 23 CONTINUE
06400 C     SET PHT1 DIAGONAL ELEMENTS EQUAL TO ONE
06410      PHT1(T,T)=1.
06420 21 CONTINUE
06430 C     SET Q MATRIX COMPUTATION INTERVAL COUNTER TO ZERO
06440      KDELT=0
06450 C     SET Q MATRIX ELEMENTS TO ZERO
06460      DO 10 T=1,7
06470      DO 10 J=1,7
06480 10   Q(T,J)=0.
06490      RETURN

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06500      END
06510 C
06520 C
06530      SUBROUTINE INITIAL
06540      COMMON/1/NG,NDELP,NN1
06550      COMMON/2/TIME,TG,TF,DELT,KDELT,X1(4),X1L(4)
06560      COMMON/3/PIMUL(12),TAJ(3,6),WM(6),DRFT(6),GY(9,6)
06570      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
06580      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
06590      COMMON/6/NTP,1CAT,NO,YL(2,2)
06600      COMMON/8/P(7,7),K(2,2),AK(8,2),HMAT(2,7)
06610      DIMENSION TP1(3,3),TP2(3,3),TP3(3,12),TP4(6,3)
06620 C      COMPUTE GYRO WEIGHTING MATRIX, TAU
06630      DO 12 I=1,NG
06640      DO 12 J=1,3
06650 12   TP4(I,J)=(1.+GY(2,I))*GY(3+J,I)
06660      DO 10 I=1,3
06670      DO 10 J=1,3
06680      TP1(I,J)=0.
06690      DO 10 K=1,NC
06700      TP1(I,J)=TP1(I,J)+TP4(K,I)*TP4(K,J)
06710 10   CONTINUE
06720      DEL=TP3(1,1)*TP1(2,2)*TP1(3,3)+TP1(1,2)*TP1(2,3)*TP1(3,1)
06730      1+TP1(1,3)*TP1(2,1)*TP1(3,2)-TP1(1,3)*TP1(2,2)*TP1(3,1)
06740      2-TP1(1,1)*TP1(2,3)*TP1(3,2)-TP1(1,2)*TP1(2,1)*TP1(3,3)
06750      DL=1./DEL
06760      TP2(1,1)=(TP1(2,2)*TP1(3,3)-TP1(3,2)*TP1(2,3))*DL
06770      TP2(1,2)=(TP1(3,2)*TP1(1,3)-TP1(1,2)*TP1(3,3))*DL
06780      TP2(1,3)=(TP1(1,2)*TP1(2,3)-TP1(2,2)*TP1(1,3))*DL
06790      TP2(2,1)=(TP1(3,1)*TP1(2,3)-TP1(2,1)*TP1(3,3))*DL
06800      TP2(2,2)=(TP1(1,1)*TP1(3,3)-TP1(1,3)*TP1(3,1))*DL
06810      TP2(2,3)=(TP1(2,1)*TP1(1,3)-TP1(1,1)*TP1(2,3))*DL
06820      TP2(3,1)=(TP1(2,1)*TP1(3,2)-TP1(3,1)*TP1(2,2))*DL
06830      TP2(3,2)=(TP1(3,1)*TP1(1,2)-TP1(1,1)*TP1(3,2))*DL
06840      TP2(3,3)=(TP1(1,1)*TP1(2,2)-TP1(2,1)*TP1(1,2))*DL
06850      DO 15 I=1,3
06860      DO 15 J=1,NG
06870      TAU(I,J)=0.
06880      DO 15 K=1,3
06890      TAU(I,J)=TAU(I,J)+TP2(I,K)*TP4(J,K)
06900 15   CONTINUE
06910 C      INITALIZE PAST DATA

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06930      DD 20 I=1,NG
06950  20  DRFT(I)=GY(1,I)
06960      DD 30 I=1,3
06980  30  WP(I,1)=WP(I,2)=PP(I)
06990 C   COMPUTE INITIAL GYRDPACK PARAMETERS, PIMU
07010      DD 40 I=1,3
07020      PIMU(I)=0.
07030      DD 40 J=1,NG
07040      PIMU(I)=PIMU(I)+TAU(I,J)*(1.+GY(2,J))*GY(1,J)
07050  40  CONTINUE
07070      L=3
07080      DD 50 I=1,3
07090      DD 60 J=1,3
07100      L=L+1
07110      PIMU(L)=0.
07120      DD 60 K1=1,NG
07130      PIMU(L)=PIMU(L)+TAU(I,K1)*(1.+GY(2,K1))*GY(3+J,K1)
07140  60  CONTINUE
07150      PIMU(4*I)=PIMU(4*I)-1.
07160  50  CONTINUE
07170 C   COMPUTE TAU*TAU-T*SIG-SQ FOR USE IN Q
07180      DD 65 J=1,NG
07190      TP3=SQRT(GY(7,J)**2*100.00*DELT+GY(9,J)**2) /100./DELT
07200      DD 65 I=1,3
07210      TP(I,J+6)=TAU(I,J)*GY(8,J) *SQRT(100.*DELT)
07220  65  TP(I,J)=TAU(I,J)*TP3
07230      DD 70 I=1,3
07240      DD 70 J=1,3
07250      OO(I,J)=0.
07260      OO(I,J+3)=0.
07270      DD 70 K=1,NG
07280      OO(I,J+3)=OO(I,J+3)+TP(I,K+6)*TP(J,K+6)
07290  70  OO(I,J)=OO(I,J)+TP(I,K)*TP(J,K)*2500.*DELT*DELT
07370 C   CONVERT UPPER LEFT 3 BY 3 OF P MATRIX TO EULER SYMMETRIC
07380 C   PARAMETER FORM. ORIGINAL P ASSUMED DIAGONAL.
07390      Z1=P(1,1)
07400      Z2=P(2,2)
07410      Z3=P(3,3)
07420      P(1,1)=.25*(Z1*X1(4)**2+Z2*X1(3)**2+Z3*X1(2)**2)
07430      P(1,2)=P(2,1)=.25*((Z1-Z2)*X1(4)*X1(3)-Z3*X1(1)*X1(2))
07440      P(1,3)=P(3,1)=.25*((Z3-Z1)*X1(4)*X1(2)-Z2*X1(1)*X1(3))
07450      P(2,2)=.25*(Z1*X1(3)**2+Z2*X1(4)**2+Z3*X1(1)**2)

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07460      P(2,3)=P(3,2)=.25*((Z2-Z3)*X1(1)*X1(4)-Z1*X1(2)*X1(3))
07470      P(3,2)=.25*(Z1*X1(2)**2+Z2*X1(1)**2+Z3*X1(4)**2)
07600      RETURN
07610      END
07620 C
07630 C
07640      SUBROUTINE STRCHK(YG)
07650      COMMON/1/NG,NDELP,NN1
07660      COMMON/2/TIME,T0,TF,DELT,KDELT,X1(4),X1L(4)
07670      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
07680      COMMON/6/NTR,ICAT,NO,YL(2,2)
07690      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
07700      ICAT=2
07710      IF(YG.GT..1) ICAT=1
07720      IF(YG.LT.-.1) ICAT=3
07880 100  CONTINUE
07890      YL(1,1)=YL(1,2)=Y(1,1)=YD(1,1)=YD(1,2)=Y(1,2)
07900      YL(2,1)=YL(2,2)=Y(2,1)=YD(2,1)=YD(2,2)=Y(2,2)
07910      RETURN
07920      END
07930 C
07940 C
07950      SUBROUTINE STARDC(C,ISTR,TBL)
07960      COMMON/2/TIME,T0,TF,DELT,KDELT,X1(4),X1L(4)
07970      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
07980      DIMENSION C(3),TP(3,3),RN(3),D(3)
07990 C      DEFINE STAR DIR. COS. IN LAB AXES
08000      TP(1,1)=-.6286902
08010      TP(1,2)= 4.7424E-5
08020      TP(2,1)=-.8544475
08030      TP(2,2)=2.153E-5
08050      TP(3,1)=-1.020237
08060      TP(3,2)= 4.512E-5
08080      CALL TRNS
08082      TT=?.*TP(ISTR,1)
08084      TW=TP(ISTR,2)+TBL
08086      D(1)=-STN(TT)*COS(TW)
08088      D(2)=STN(TT)*SIN(TW)
08090      D(3)=COS(TT)
08180 C      FORM LAB INERTIAL ATTITUDE
08190      CALL LABATT
08200 C      CONVERT TO INERTIAL COORD.

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08210      DO 20 I=1,3
08220      C(I)=0.
08230      DO 20 J=1,3
08240 20   C(I)=C(I)+R(J,I,2)*D(J)
08250      RETURN
08260      END
08270 C
08280 C
08290      SUBROUTINE LABATT
08300      COMMON/2/TIME,TO,IE,DELT,KDFLT,X1(4),X1L(4)
08310      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
08320      RTA=1.-COS(7.27220522E-5*TIME)
08330      R1=0.
08340      R2=0.929988941
08350      R3=0.557791899
08360      AL=SIN(7.27220522E-5*TIME)
08370      B(1,1,2)=1.-RTA*(R2**2+R3**2)
08380      B(1,2,2)=AL*R3+RTA*R1*R2
08390      B(1,3,2)=-AL*R2+RTA*(1*R3
08400      B(2,1,2)=-AL*R3+RTA*R1*R2
08410      B(2,2,2)=1.-RTA*(R1**2+R3**2)
08420      B(2,3,2)=AL*R1+RTA*R2*R3
08430      B(3,1,2)=AL*R2+RTA*R1*R3
08440      B(3,2,2)=-AL*R1+RTA*R2*R3
08450      B(3,3,2)=1.-RTA*(R1**2+R2**2)
08460      RETURN
08470      END
08480 C
08490 C
08500      SUBROUTINE GYPCK
08510      COMMON/1/NG,NOELP,NNI
08520      COMMON/3/PTMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
08530      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),QO(4,6),WR(3,2),RP(4,4)
08540      DIMENSION TP(3)
08550      PROVIDES ESTIMATED S/C RATES BASED UPON COMPENSATED GYROS.
08560      DO 10 T=1,3
08570      SHFTS PREVIOUS RATE DATA BACK ONE STEP
08580      WR(T,2)=WR(T,1)
08590      COMPUTE NEW GYRO PACKAGE RATE ESTIMATE
08600      TP(T)=-PTMU(1)
08610      DO 10 J=1,NG
08620      TP(T)=TP(T)+IAL(I,J)*WM(J)

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08780 10 CONTINUE
08790   L=3
08800   DO 20 T=1,3
08810     WR(I,1)=TP(I)
08820   DO 20 J=1,3
08830     L=L+1
08840     WD(T,1)=WR(I,1)-PINU(L)*TP(J)
08850 20 CONTINUE
08860   PFTUPN
08870   FND
08880 C
08890 C
09220   SUBROUTINE ATT
09230 C   PERFORMS NUMERICAL INTEGRATION TO DETERMINE SPACECRAFT ATTITUDE
09240 C   AS REPRESENTED BY EULER SYMMETRIC PARAMETERS
09250   COMMON/2/TIME,TO,TF,DELT,KDEL1,X1(4),X1L(4)
09260   COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
09270   DIMENSION T(5),TP(3)
09280   DO 20 I=1,3
09290 20 TP(I)=.5*(WR(I,1)+WR(I,2))
09300 C   COMPUTE S(0) FOR USE IN RP MATRIX
09310   T(2)=(TP(1)**2+TP(2)**2+TP(3)**2)*DELT**2/4,
09320   T(1)=SQRT(T(2))
09330   T(2)=COS(T(1))
09340   T(3)=.5
09350   IF(ABS(T(1)).LE.1.E-20) GO TO 6
09360   T(3)=SIN(T(1))
09370   T(3)=T(3)/(2.*T(1))
09380 6 CONTINUE
09390 C   FORM RP MATRIX FOR PROPAGATING EULER PARAMETERS
09400   RP(1,2)=T(3)*TP(3)*DELT
09410   RP(1,3)=-T(3)*TP(2)*DELT
09420   RP(1,4)=T(3)*TP(1)*DELT
09430   RP(2,3)=RP(1,4)
09440   RP(2,4)=-RP(1,3)
09450   RP(3,4)=RP(1,2)
09460   DO 10 I=1,4
09470     RP(I,I)=-T(2)
09480   DO 10 J=1,T
09490     RP(T,J)=-RP(J,I)
09500 10 CONTINUE
09530   CALL PHT

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09550 C      PROPAGATE EULER PARAMETERS
09560      DO 12 I=1,4
09570      T(T)=0.
09580      DO 12 J=1,4
09590      T(J)=T(I)+RP(I,J)*X1(J)
09600 12 CONTINUE
09610 C      NORMALIZE EULER PARAMETERS
09620      T(5) = SORT(T(1)**2+T(2)**2+T(3)**2+T(4)**2)
09630      DO 14 I=1,4
09640      X1(I)=T(I)/T(5)
09650 14 CONTINUE
09660      RETURN
09670      END
09680 C
09690 C      SUBROUTINE PHI
09700 C      COMPUTES THE STATE TRANSITION MATRICES PHI1 AND PHI2
09710 C      COMMON/I/NG,NDELP,NN1
09720 C      COMMON/2/TIME,T0,TF,DELT,KDELT,X1(4),X1L(4)
09730 C      COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),QD(4,6),WR(3,2),RP(4,4)
09740 C      DIMENSION W(4),T1(3,12),PK(4,3),PHI2T(4,12),TP1(7,7),TP2(7,7)
09750 C      DIMENSION P0(7,7)
09760 C      COMPUTE PHI1
09770 C      DO 10 J=1,4
09780      DO 11 I=1,4
09790      W(I)=0.
09800      DO 11 K=1,4
09810      W(I)=W(I)+PP(I,K)*PHI1(K,J)
09820 11 CONTINUE
09830      PHI1(T,J)=W(1)
09840 10 CONTINUE
09850 C      COMPUTE PHI2
09860      DO 42 T=1,4
09870      DO 42 J=1,NN1
09880      PHI2T(T,J)=0.
09890      DO 42 K=1,4
09900 42      PHI2T(T,J)=PHI2T(I,J)+RP(I,K)*PHI2(K,J)
09910      DO 14 T=1,3
09920      PK(T,T)=X1(4)
09930 14      CONTINUE
09940      PK(1,2)=-X1(3)
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09980      PK(1,3)=X1(2)
09990      PK(2,3)=-X1(1)
10000      PK(2,1)=X1(2)
10010      PK(3,1)=-X1(2)
10020      PK(3,2)=X1(1)
10030      PK(4,1)=-X1(1)
10040      PK(4,2) = -X1(2)
10050      PK(4,3)=-X1(3)
10060      DO 30 I=1,3
10070      DO 31 J=1,3
10080 . 31   T1(I,J)=0.
10090  30   T1(I,I)=-1.
10210      J1=1
10220      DO 19 J = 1,3
10250      DO 22 I=1,4
10260      TZ = 0.
10270      DO 23 K=1,3
10280      TZ = TZ+PK(T,K)*T1(K,J)
10290      23 CONTINUE
10300      PHI2(T,J1) = PHI2T(I,J1)+TZ
10310      22 CONTINUE
10320      J1=J1+1
10330      19 CONTINUE
10350 C      UPDATE 0 IF TIME IS APPROPRIATE
10360      KDELT=KDELT+1
10370      IF(KDELT.LT.100) GO TO 50
10380      KDELT=0
10390      DO 55 T=1,4
10400      DO 55 J=1,3
10410      TP2(T,J)=0.
10420      DO 55 K=1,3
10430  55   TP2(I,J)=TP2(I,J)+PK(I,K)*Q0(K,J)
10440      DO 60 T=1,4
10450      DO 60 J=1,4
10460      TP1(I,J)=0.
10470      DO 60 K=1,3
10480  60   TP1(T,J)=TP1(I,J)+TP2(I,K)*PK(J,K)
10490      DO 61 T=5,7
10500      DO 61 J=1,4
10510  61   TP1(I,J)=TP1(J,I)=0.
10520      DO 62 T=5,7
10530      DO 62 J=5,7

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10540   62  TP1(I,J)=Q0(I-4,J-1)
10550   T9=PP(2,1)**2+RF(3,1)**2+RP(4,1)**2
10560   T9=SOPT(1,-10000.*T9)
10570   DO 43 J=1,4
10580   DD 64 J=1,4
10590   R0(I,J)=RP(I,J)*100.
10600   64  R0(I+3,J)=0.
10610   DD 65 J=1,3
10620   R0(I,J+4)=-DELT*PK(I,J)*50.
10630   65  R0(I+3,J+4)=0.
10640   R0(I+3,I+3)=1.
10650   R0(I,I)=T9
10660   63  CONTINUE
10670   DD 56 I=1,7
10680   DD 55 J=1,7
10690   TP2(I,J)=0.
10700   DD 66 K=1,7
10710   66  TP2(I,J)=TP2(I,J)+Q(I,K)*R0(J,K)
10720   DD 67 J=1,7
10730   DD 67 J=1,7
10740   Q(I,J)=TP1(I,J)
10750   DD 67 K=1,7
10760   67  Q(I,J)=Q(I,J)+R0(I,K)*TP2(K,J)
10770   50  CONTINUE
10780 C  PHI2 MUST STILL BE MULTIPLIED BY DELT/2 IN PRFIL
10790   RETURN
10800   END
10810 C
10820 C
10830   SURROUTINE QMAT
10840 C  FORM THE STATE NOISE COVARIANCE MATRIX
10850   COMMON/1/NG,NDelp,NN1
10860   COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),Q0(4,6),WR(3,2),RP(4,4)
10870   DIMENSION TP1(7,7)
10880 C  PROPERLY PACK Q MATRIX
10890   DD 10 I=1,7
10900   DD 10 J=1,7
10910   10  TP1(I,J)=Q(I,J)
10920   J3=?
10930   DD 15 I=1,3
10940   J1=?
10950   DD 17 J=1,3

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10970      J1=J1+1
10980      O(T,J1)=O(J1,I)=TP1(I,J+4)
10990 17. CONTINUE
11010      J3=J3+1
11020      J2=3
11030      DO 16 J=1,3
11050      J2=J2+1
11060      O(J3,J2)=TP1(I+4,J+4)
11070 16. CONTINUE
11080 15. CONTINUE
11160      RETURN
11170      END
11180 C
11190 C
11200      SUBROUTINE TRAC(YG)
11210      COMPUTES TRACKER OUTPUT ANGLES FROM ATTITUDE AND
11220      TRACKER IDENTIFICATION NUMBER
11230      COMMON/2/TTME,TO,TF,DELT,KDELT,X1(4),X1L(4)
11240      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
11250      COMMON/6/NTR,ICAT,NO,YL(2,2)
11260      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
11270      DIMENSION T(5),C(3,3),TT(3)
11280      YL(1,1)=Y(1,1)
11290      YL(2,1)=Y(2,1)
11300      CALL TRNS
11400 C      COMPUTE TRACKER TRANSFORMATION RELATIVE TO INERTIAL COORD
11410      DO 80 I=1,3
11420      DO 80 J=1,3
11430      C(I,J)=0.
11440      DO 80 K=1,3
11450      C(I,J) = C(I,J)+AST(I,K,NO)*B(K,J,1)
11460 80. CONTINUE
11470 C      COMPUTE STAR DIRECTION COSINES IN TRACKER AXES
11480      DO 90 I=1,3
11490      U(I) = C(I,1)*STR(1,1)+C(I,2)*STR(2,1)+C(I,3)*STR(3,1)
11500 90. CONTINUE
11630      U(5)=SQRT(1.-U(1)**2)
11820 C      COMPUTE TRACKER OUTPUT IF IT HAD INFINITE BANDWIDTH (INTERVAL AVE.)
11830      Y(1,1)=-(U(1)+SIN(YG))/U(5)-(SSV(4,1)+SSV(5,1))
11840      Y(2,1)=U(3)-(SSV(3,1)+U(5)+SSV(1,1)-U(1)*SSV(2,1))

11890 100 RETURN

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11900      END
11910 C
11920 C
11930      SUBROUTINE TRCFLT
11940      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
11950      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
11960      COMMON/6/NTR,ICAT,NO,YL(2,2)
11970      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
11980      DIMENSION C(2),R(2)
11990 C      PRINTS FILTERED TRACKER OUTPUT
12000      C(1)=SSV( 8,NO)/DELT
12010      C(2)=SSV( 9,NC)/DELT
12020      R(1)=EXP(-1./C(1))
12030      R(2)=EXP(-1./C(2))
12040      DO 10 K=1,2
12050      DO 10 T=1,2
12060      10 YD(I,K)=YD(I,K)*R(I)+(1.-C(I))*(1.-R(I))*Y(I,K)
12070      1+(C(I)*(1.-R(I))-R(I))*YL(I,K)
12080      RETURN
12090      END
12100 C
12110 C
12120      SUBROUTINE PRFIL
12130 C      CONVERTS 4-PARAMETER ATTITUDE SYSTEM TO 3 PARAMETERS AND MODIFIES
12140 C      STATE TRANSITION MATRIX
12150      COMMON/1/NG,NOELP,NN1
12160      COMMON/2/TIME,TO,TF,DELT,KDELT,X1(4),X1L(4)
12170      COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
12180      COMMON/4/PHT1(4,4),PHI2(4,3),Q(7,7),OO(4,6),WR(3,2),RP(4,4)
12190      COMMON/5/SSV(27,2),PP(3),B(3,3,2)
12200      COMMON/6/NTR,ICAT,NO,YL(2,2)
12210      COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
12220      COMMON/R/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
12230      DIMENSION W(3)
12240      W(1)=X1L(1)/X1L(4)
12250      W(2)=X1L(2)/X1L(4)
12260      W(3)=X1L(3)/X1L(4)
12270      DO 10 T=1,3
12280      DO 10 J=1,3
12290      PHT1(T,J)=PHT1(1,J)-PHT1(1,4)*W(J)
12300      10 CONTINUE
12310      DO 12 T=1,3

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12320    DD 12 J=1,NN1
12330    PHI2(T,J)=PHI12(I,J)+DELT/2.
12340    12 CONTINUE
12350    RETURN
12360    END
12370 C
12380 C
12390    SUBROUTINE HMTX
12400 C COMPUTES MEASUREMENT MATRIX
12410 COMMON/1/NG,INDELP,NN1
12420 COMMON/2/TIME,T0,TF,DELT,KDELT,X1(4),X1L(4)
12430 COMMON/6/NTR,ICAT,NO,YL(2,2)
12440 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
12450 COMMON/P/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
12460 DIMENSION T(3),TT(4,4),T1(3,4)
12470 DIMENSION TA(2,4)
12780 DO 130 I=1,4
12790 TT(I,I)=0.
12800 130 CONTINUE
12810 TT(1,2) = -STR(3,1)
12820 TT(1,3) = STR(2,1)
12830 TT(1,4) = STR(1,1)
12840 TT(2,3) = -STR(1,1)
12850 TT(2,4) = STR(2,1)
12860 TT(3,4) = STR(3,1)
12870 TT(2,1) = -TT(1,2)
12880 TT(3,1) = -TT(1,3)
12890 TT(3,2) = -TT(2,3)
12900 TT(4,1) = TT(1,4)
12910 TT(4,2) = TT(2,4)
12920 TT(4,3) = TT(3,4)
12930 T(1) = -X1(1)/X1(4)
12940 T(2) = -X1(2)/X1(4)
12950 T(3) = -X1(3)/X1(4)
12960 DO 160 I=1,3
12970 DO 160 J=1,3
12980    TT(I,J) = TT(I,J)+STR(I,1)*T(J)
12990 160 CONTINUE
13000 DO 165 T=1,?
13010    T1(T,1) = (-AST(1,1,NO)*X1(4)+AST(1,2,NO)*X1(3)
13020    1-AST(T,3,NO)*X1(2))*2.
13030    T1(T,?) = (-AST(I,1,NO)*X1(3)-AST(I,2,NO)*X1(4)

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13040    I+AST(I,3,NO)*X1(1))*2.
13050    T1(T,3) = (AST(I,1,NO)*X1(2)-AST(I,2,NO)*X1(1)
13060    I-AST(I,3,NO)*X1(4))*2.
13070    T1(T,4) = (-AST(I,1,NO)*X1(1)-AST(I,2,NO)*X1(2)
13080    I-AST(I,3,NO)*X1(3))*2.
13090 165 CONTINUE
13100  DO 166 K=1,4
13110    TA(1,K)=T1(1,K)/SQR1(1.-U(1)**2)
13120    TA(2,K)=-T1(3,K)
13130 166 CONTINUE
13140  DO 180 J=1,3
13150    HMAT(1,J)=0.
13160    HMAT(2,J)=0.
13170  DO 180 K=1,4
13180    HMAT(1,J)=HMAT(1,J)+TA(1,K)*TT(K,J)
13190    HMAT(2,J)=HMAT(2,J)+TA(2,K)*TT(K,J)
13200 180 CONTINUE
13210  RETURN
13220 END
13230 C
13240 C
13250 SUBROUTINE RMAT
13260 C FORMS MEASUREMENT NOISE COVARIANCE MATRIX
13270 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
13280 COMMON/6/NTR,ICAT,NO,YL(2,2)
13290 COMMON/R/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
13300 R(1,2)=R(2,1)=0.
13310 R(1,1)=SSV( 6,NO)**2
13320 R(2,2)=SSV( 7,NO)**2
13330 RETURN
13340 END
13350 C
13360 C
13370 SUBROUTINE FILT
13380 C USING KALMAN FILTER EQS., COMPUTES FILTER GAINS,AK, AND PROPAGATES
13390 C ERROR COVARIANCE MATRIX,P
13400 COMMON/1/NG,NDELP,NN1
13410 COMMON/?/PTMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
13420 COMMON/4/PHI1(4,4),PHI2(4,3),Q(7,7),WQ(4,6),WR(3,2),RP(4,4)
13430 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
13440 COMMON/R/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
13450 DIMENSION TA(7,7),TB(7)

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13460 C COMPUTE ADDITIONAL CONSTANTS FOR PARTITIONING MATRICES
13465 NN2=NN1
13470 MN3=NN1-MN2
13480 N=NN1+3
13490 M=2
13500 CALL SRMMUL(PHI1,1,1,3,3,P,1,1,3,TA,1,1,4,7,7)
13510 CALL SPMMUL(PHI2,1,1,3,NN2,P,4,1,3,P,1,1,4,7,7)
13520 CALL SPMADD(TA,1,1,P,1,1,TA,1,1,3,3,7,7,7)
13530 CALL SPMMUL(PHI1,1,1,3,3,P,1,4,NN2,TA,1,4,4,7,7)
13540 CALL SPMMUL(PHI2,1,1,3,NN2,P,4,4,NN2,P,1,4,4,7,7)
13550 CALL SPMADD(TA,1,4,P,1,4,P,1,4,3,NN2,7,7,7)
13560 CALL SRMMUL(PHI1,1,1,3,3,P,1,4+NN2,NN3,TA,1,4+NN2,4,7,7)
13570 CALL SPMMUL(PHI2,1,1,3,NN2,P,4,4+NN2,NN3,P,1,4+NN2,4,7,7)
13580 I1=4+NN2
13590 CALL SPMADD(TA,1,I1,P,1,I1,P,1,I1,3,NN3,7,7,7)
13600 DO 15 T=1,3
13610 DO 15 K=1,3
13620 P(I,K)=0.
13630 DO 15 J=1,3
13640 15 P(I,K)=P(I,K)+TA(I,J)*PHI1(K,J)
13650 DO 20 I=1,3
13660 DO 20 K=1,3
13670 TA(I,K)=0.
13680 DO 20 J=1,NN2
13690 20 TA(I,K)=TA(I,K)+P(I,J+3)*PHI2(K,J)
13700 CALL SPMADD(P,1,1,TA,1,1,P,1,1,3,3,7,7,7)
13710 CALL SPMTRA(P,1,4,3,NN2,P,4,1,7,7)
13720 CALL SPMTPA(P,1,4+NN2,3,NN3,P,4+NN2,1,7,7)
13730 C P=PHT P PHI-TRANSPOSE HAS BEEN COMPUTED
13740 CALL SPMADD(P,1,1,Q,1,1,P,1,1,N,N,7,7,7)
13750 RETURN
13760 ENTRY FFILT
13770 CALL SPMMUL(HMAT,1,1,M,N,P,1,1,N,TA,1,1,2,7,7)
13780 CALL SPMTRA(HMAT,1,1,M,N,AK,1,1,2,8)
13790 CALL SRMMUL(TA,1,1,M,N,AK,1,1,M,TA,M+1,1,7,8,7)
13800 CALL SPMADD(TA,M+1,1,R,1,1,TA,1,1,M,M,7,2,7)
13810 C INVERSE ROUTINE FOLLOWS
13820 DET=TA(1,1)*TA(2,2)-TA(2,1)*TA(1,2)
13830 TA(1,M+1)=TA(2,2)/DET
13840 TA(1,M+2)=-TA(1,2)/DET
13850 TA(2,M+1)=-TA(2,1)/DET
13860 TA(2,M+2)=TA(1,1)/DET

```

```

13870 C    END OF INVERSE ROUTINE
13880     CALL SRMMUL(AK,1,1,N,M,TA,1,M+1,M,TA,1,1,8,7,7)
13890     CALL SRMMUL(P,1,1,N,N,TA,1,1,M,AK,1,1,7,7,8)
13900 C    AK HAS BEEN COMPUTED
13910     DO 45 I=1,N
13920     DO 45 K=1,N
13930     TA(I,K)=0.
13940     DO 40 J=1,M
13950     40 TA(I,K) = TA(1,K)-AK(I,J)*HMAT(J,K)
13960     IF (I.NE.K) GO TO 45
13970     TA(I,K) = 1.+TA(I,K)
13980     45 CONTINUE
13990     DO 55 T=1,N
14000     DO 50 K=1,N
14010     TR(K)=0.
14020     DO 50 J=1,N
14030     50 TR(K)=TR(K)+TA(I,J)*P(J,K)
14040     DO 55 K=1,N
14050     55 TA(I,K)=TR(K)
14060 C    SYMMETRIZE ERROR COVARIANCE MATRIX
14070     DO 60 I=1,N
14080     DO 60 J=1,N
14090     60 P(I,J)=0.5*(TA(I,J)+TA(J,I))
14100 C    P(K+1) HAS BEEN COMPUTED
14110     RETURN
14120     END
14130 C
14140 C
14150     SUBROUTINE SRMMUL(A,IMA,INA,MA,NA,B,IMB,INB,NB,C,IMC,INC,IRA,IRB,
14160     1IPC)
14170 C    C=A*B WITH TNIT. ARRAY ELEMENTS SPECIFIED
14180     DIMENSION A(49),B(49),C(49)
14190     DO 5 I=1,MA
14200     IPTMC = I+IMC
14210     IPTMA = I+IMA
14220     IF (NA.LT.1) GO TO 6
14230     DO 5 K=1,NA
14240     KPTMC = K+IMC
14250     KPTNB = K+INB
14260     IC = IPTMC-1+(KFINC-2)+IRC
14270     C(IC) = 0.
14280     IF (NA.LT.1) GO TO 6

```

```

14290    DO 5 J=J,NA
14300    JPINA = J+JNA
14310    JPIMR = J+JMB
14320    IA = JPIMA-1+(JPINA-2)*IRA
14330    IB = JPIMB-1+(JPINB-2)*IRB
14340    5 C(IC) = C(IC)+A(IA)*B(IB)
14350    6 RETURN
14360    END
14370 C
14380 C
14390    SUBROUTINE SRMADD(A,IMA,INA,B,IMB,INB,C,IMC,INC,M,N,IRA,IRB,IRC)
14400 C   C=A+B WITH INIT. ARRAY ELEMENTS SPECIFIED
14410    DIMENSION A(49),B(49),C(49)
14420    DO 5 T=1,M
14430    IF (N.LT.1) GO TO 6
14440    DO 5 J=1,N
14450    IPIMC = I+IMC
14460    JPINC = J+INC
14470    IPIMA = I+IMA
14480    JPINA = J+INA
14490    IPIMH = I+TMB
14500    JPINR = J+INB
14510    IA = IPIMA-1+(JPINA-2)*IRA
14520    IB = IPIMB-1+(JPINB-2)*IRB
14530    IC = IPIMC-1+(JPINC-2)*IRC
14540    5 C(IC) = A(IA)+B(IB)
14550    6 RETURN
14560    END
14570 C
14580 C
14590    SUBROUTINE SRMTRA(A,IMA,INA,M,N,B,IMB,INB,IRA,IRB)
14600    DIMENSION A(49),B(49)
14610 C   B=A-TRANPOSE WITH INIT. ARRAY ELEMENTS SPECIFIED
14620    IF (N.LT.1) GO TO 6
14630    DO 5 I=1,N
14640    DO 5 J=1,M
14650    JPIMR = I+JMB
14660    JPTMR = J+JMB
14670    JPIMA = J+IMA
14680    JPINA = I+INA
14690    IA = JPIMA-1+(JPINA-2)*IRA
14700    TR = JPIMR-1+(JPINB-2)*IRE

```

```

14710      5 B(IR)=A(IA)
14720      6 RETURN
14730      END
14740 C
14750 C
14760 SUBROUTINE POFIL
14770 C UPDATES ATTITUDE VARIABLES AND OTHER SYSTEM ELEMENTS OF THE
14780 C STATE VECTOR
14790 COMMON/1/NG,NDELP,NN1
14800 COMMON/2/TTME,T0,TE,DELT,KDELI,X1(4),X1L(4)
14810 COMMON/3/PIMU(12),TAU(3,6),WM(6),DRFT(6),GY(9,6)
14820 COMMON/5/SSV(27,2),PP(3),B(3,3,2)
14830 COMMON/7/YD(2,2),Y(2,2),U(15),AST(3,3,2),STR(3,2)
14840 COMMON/8/P(7,7),R(2,2),AK(8,2),HMAT(2,7)
14850 DIMENSION W(3),T(3)
14860 W(1)=YD(1,2)-YD(1,1)
14870 W(2)=YD(2,2)-YD(2,1)
14900 C COMPUTE CORRECTION FOR EACH SYSTEM PARAMETER OF STATE VECTOR
14910 DO 11 I=1,NN1
14920 W(3) = AK(I+3,1)*W(1)+AK(I+3,2)*W(2)
15020 PIMU(T)=PIMU(1)+W(3)
15060 11 CONTINUE
15080 C COMPUTE CORRECTIONS FOR EACH ATTITUDE VARIABLE
15090 DO 9 I=1,3
15100 T(I) = AK(I,1)*W(1)+AK(I,2)*W(2)
15110 9 CONTINUE
15120 C UPDATE ATTITUDE VARIABLES
15130 X1(4)=X1(4)-(X1(1)*T(1)+X1(2)*T(2)+X1(3)*T(3))/X1(4)
15140 DO 10 I=1,3
15150 X1(I)=X1(I)+T(I)
15160 10 CONTINUE
15170 RETURN
15180 END
15190 C
15200 C

```

```

00100 PROGRAM DTAPED(INPUT,OUTPUT,TAPE1)
00110 COMMON A(300,3),N(300),LFILE
00120 DIMENSION R(3)
00125 REWIND 1
00130 I=0
00140 10 I=I+1
00150 READ(1,6) A(1,1),A(1,2),A(1,3),N(I)
00155 A(I,3)=SQRT(A(I,2)**2+A(I,3)**2)
00160 E FORMAT(3(2X,E13.6),2X,I1)
00170 TF(EOF,11) 20,10
00180 20 CONTINUE
00190 LFILE=I-1
00200 ACCEPT N1
00210 PRINT ?,N1
00220 2 FORMAT(X,RHPUN NO. ,I2)
00221 DO 100 L1=2,3
00222 PRINT 7,L1
00223 7 FORMAT(//X,I1,X,I2HAXIS RESULTS/
00224 122X,3HAV.,5X,3HRSS,4X,4HPEAK/)
00230 CALL ANAL(B,1,L1)
00240 PRINT 3,(B(I),I=1,3)
00250 3 FORMAT(16HESTIMATION ERROR,5X,3(F5.2,3X))
00260 CALL ANAL(B,2,L1)
00270 PRINT 4,(B(I),I=1,3)
00280 4 FORMAT(17HFILTER CONFIDENCE,4X,3(F5.2,3X))
00290 CALL ANAL(B,3,L1)
00292 DO 30 T=1,3
00294 30 R(I)=R(T)/4.648E-6
00300 PRINT 5,(R(I),I=1,3)
00310 5 FORMAT(14HMFAST. RESIDUAL,7X,3(F5.2,3X))
00315 100 CONTINUE
00320 END
00330 C
00340 C
00350 SUBROUTINE ANAL(B,K,L1)
00360 COMMON A(300,3),N(300),LFILE
00370 DIMENSION R(3),C(200,2)
00380 T=0
00390 DO 50 J=1,LFILE
00400 IF(N(J).NE.K) GO TO 50
00410 I=I+1
00420 C(I,1)=A(J,1)

```

```
00430      C(I,2)=A(J,L1)
00440  50  CONTINUE
00450      T1=T-1
00460      S=SM=0.
00470      T0=C(T,1)-C(1,1)
00480      SMX=C(1,2)
00490      DO 30 J=1,I1
00500      T=C(J+1,1)-C(J,1)
00510      X2=C(J+1,2)
00520      X1=C(J,2)
00530      S=S+(X1**2+X2**2+X1*X2)*T/3.
00540      SM=SM+T*(X1+X2)/2.
00550      IF(X2.LT.SMX) GO TO 30
00560      SMX=X2
00570  30  CONTINUE
00580      B(1)=SM/T0
00590      B(2)=SQRT(S/T0)
00600      B(3)=SMX
00610      RETURN
00620      END
```

APPENDIX C

CSDL GYRO REPORTS

C-4441

OAO-IRU ENGINEERING MODEL DATA
AT GODDARD SPACE FLIGHT CENTER

May 1975

by

R. CARSON

R. HARRIS

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ACKNOWLEDGEMENT

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The publication of this report does not constitute approval by NASA of the findings of the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

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1.0

INTRODUCTION

The IRU(OAO) is a three-axis strap-down inertial reference unit that was designed and built by the Charles Stark Draper Laboratory (CSDL) under contract with NASA's Goddard Space Flight Center (GSFC) for their Orbiting Astronomical Observatory. The IRU(OAO) Engineering Model was built in 1968, went through qualification testing in 1969 and was delivered to GSFC in March 1970. Since then it has been modified and used by GSFC to demonstrate various concepts.

Early in 1975 consideration was given to using the Engineering Model in a concept evaluation program to be conducted with the TRW Precision Attitude Determination System (PADS). In mid-April 1975, GSFC contracted with CSDL for the following efforts:

1. to evaluate the current performance and operating characteristics of the Engineering Model
2. to assist with the integration of the unit with the PADS if the first item shows the Engineering Model to be in satisfactory operating condition.

This report describes the first effort. Two trips were made to GSFC in support of the first item. The first trip was made from 7-10 April 1975 to investigate the modifications made by GSFC to the Engineering Model. The second trip was made from 20-23 May 1975 to take data from the system. A brief summary of both trips is included in Section 3. Section 4 contains a summary of the result for data accumulated from 20-28 May 1975. The conclusion and recommendations are reported in section 2.

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2.0

CONCLUSION AND RECOMMENDATIONS

The Engineering Model of the OAO-IRU is not operating properly. This is apparent from several system malfunctions during testing and the results of the data accumulated. Assuming, however, that the system does not degrade further, the following performance capabilities are feasible if the system is continually updated at 30 minute intervals or less.

1. Roll Axis - One sigma angle uncertainty
< 1 arc-second.
2. Pitch Axis - One sigma angle uncertainty
< 2 arc-seconds.
3. Yaw Axis - One sigma angle uncertainty
< 10 arc-seconds.

Because of abnormalities in the system data obtained (especially for the yaw axis gyro), history of system malfunctions, and the possibility of future malfunctions or failures, CSDL recommends that GSFC does not send the OAO-IRU Engineering Model to TRW for integration with the PADS system. It is believed that there is an intermittent failure either in the Precision Power Supply or Wheel Power Supply within the Electronics Package. However, identifying and correcting such a problem could be quite time consuming and unfortunately is beyond the scope of this contract.

3.0

SUMMARY OF EVENTS

The first trip was made to GSFC from 7-10 April 1975. The purpose of this trip was to investigate a possible module failure and become familiar with the modifications made by GSFC to the OAO-IRU Engineering Model. The suspect module was an MH-7 type which supplies the gyro's signal generator excitation. This module was found to be defective and was subsequently repaired by externally wiring a set of transistors to replace the defective ones within the module. This same procedure was previously used on an MH-3 type module that provides the suspension excitation. There was no apparent reason for either of these modules' demise. It is known however that the MH-3 module will self-destruct if it loses a reference frequency from the precision power supply in the electronics package. Another possible malfunction in an MD-10 type module was also noted (R-Term Pulse Generator). However, since this failure should not affect PADS testing it was not pursued. All repairs were made by GSFC technicians.

After the above repairs were made to the system, a second trip (20-23 May 1975) was made to obtain data from the IRU. The system was turned on and data acquisition was started at approximately 9 pm on 20 May 1975. At approximately 6 am on 21 May 1975 the system went into the ISTAB mode with a continuous-angle-reset commanded. This is symptomatic of a momentary loss of power. The system was reset at approximately 9 am and ran for approximately 8 hours before the same thing happened again. The power supply in the Ground Support Equipment which supplies the prime power to the IRU was then replaced and data was accumulated from Wednesday night until Thursday morning (21-22 May). No problems occurred during that period.

During Thursday the system was shut down for modifications to the IRU-PADS data interface. After those modifications were completed, the system was turned on with the IP-load panel (gyro package simulator) and the electronics package checked out. Once, while in this configuration the system went into the ISTAB mode with a continuous angle reset commanded. Also while in this mode a second anomalous behavior was observed. When the dummy wheel load was cycled on and off, the system power would frequently (approximately 50% of the time) increase by 60 watts. When this happened, the only noticeable effect was a 3 to 4 volt drop in the 45 volts which is used for the gyro torque loops. On Thursday pm (22 May) the IRU was again turned on with the Inertial Package and data was accumulated until 2:30 pm on 28 May 1975 without any further visible abnormalities.

4.0 SUMMARY OF RESULTS

Two types of data were accumulated during the period from 20-28 May 1975.

- (1) Long Term Stability data where the net number of rebalance torque pulses were calculated and recorded every 2.56 or 20.48 seconds.
- (2) Noise Equivalent Angle data where each 5 millisecond rebalance pulse was recorded.

4.1 Long Term Stability Data

Three sets of long term data were recorded for each gyro. The periods over which each set of data was taken are listed below.

- (1) Set 1 9 pm 20 May to 9 am 21 May 1975.
- (2) Set 2 9 pm 21 May to 9 am 22 May 1975.
- (3) Set 3 11 pm 22 May to 2:30 pm 28 May 1975.

Figures 1 through 3 show the results of set 1 for the roll, pitch, and yaw axis respectively. This data was processed by calculating the average rate every 71.68 seconds. Figure 4 is the output of a tiltmeter whose sensitive axis was about a NW-SE line.

These plots reveal the following:

- (1)*Rate impulses in the roll axis output that occur every 1/2 to 1 hour and have a magnitude of 0.2 to 0.3 meru.
- (2) Several small changes in level (0.1 to 0.2 meru) and one large change of about 0.5 meru in the pitch axis.
- (3) Very erratic behavior of the yaw axis with peak-to-peak changes of 1.5 meru.
- (4) The tiltmeter data is quiet and well behaved thus eliminating base motion as a source of the gyros' behavior.

Figures 5 through 8 are the results of data set 2 and were processed as set 1. Again each instrument has its own unique behavior. Figure 9 through 11 are the results of data set 3. This data is a graphical presentation of the average

* This data without the presence of the rate impulses is characteristic of the performance of each instrument when the IRU is operating properly.

rate over every 675.84 seconds. The spikes in fig 10 (pitch axis) are a result of a data acquisition malfunction. This data again is consistent with that previously obtained even though no visible system malfunctions occurred. Data set 3 also shows the following long term characteristics of each instrument.

- (1) The roll gyro is fairly well behaved except for the existence of rate impulses (.2 to .3 meru) occurring every 1/2 to 1 hour.
- (2) The pitch gyro exhibits discrete changes in the rate output with a peak amplitude of 1 meru. These changes are very regular and have a periodicity of \sim 16 hours.
- (3) The yaw gyro is extremely erratic with peak to peak changes in rate of approximately 7.5 meru.

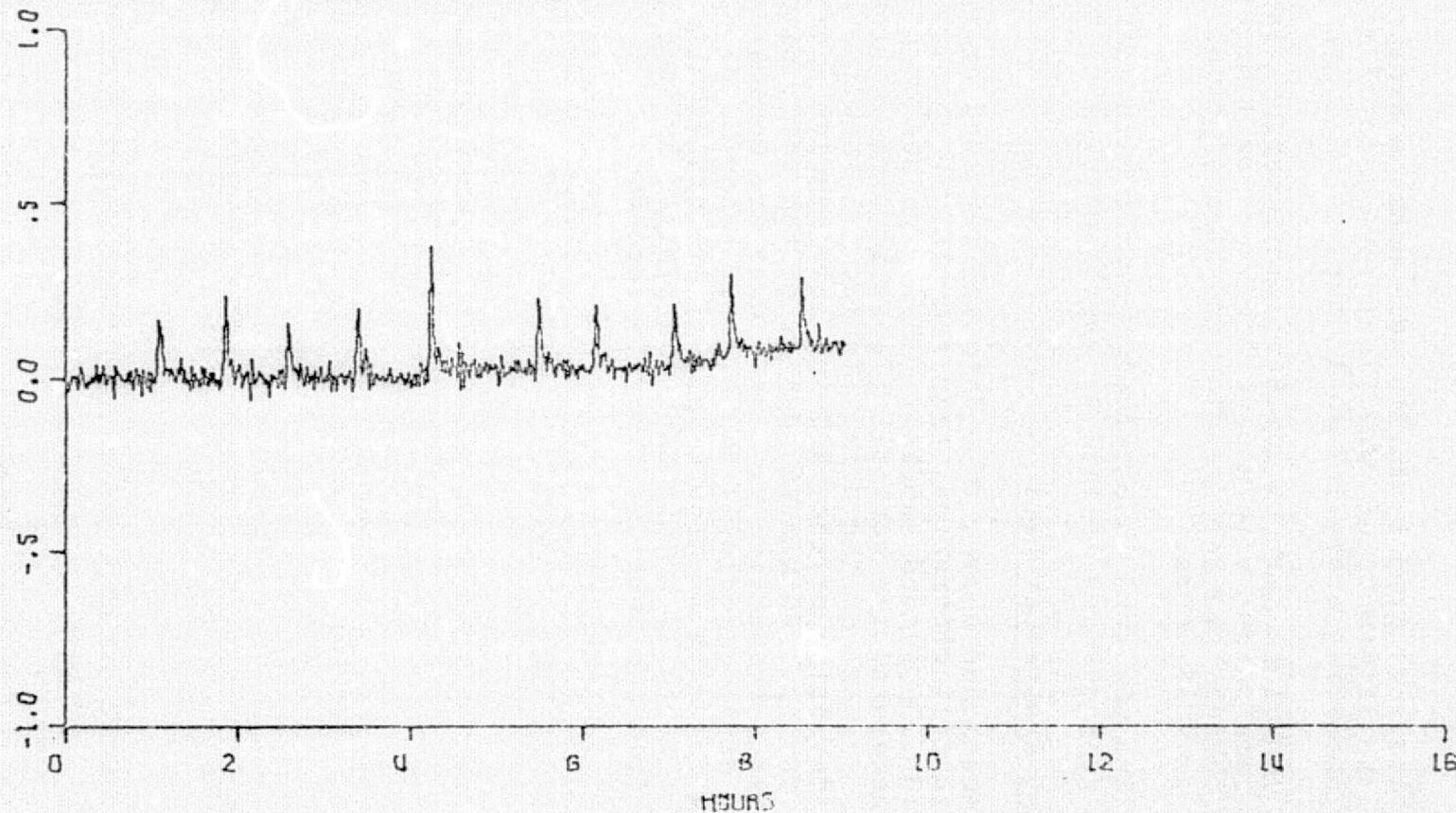
4.2 Noise Equivalent Data

As mentioned above, this data was recorded every .005 seconds. To fulfill contractual requirements, 40 samples were summed to yield .200 second samples. This data was then processed to determine the best fit (least squares) attitude for each 30 minute segment of the data. Tables 1-3 show the peak and one sigma deviation of the .200 sec data samples from the best fit data for each 30 minute segment of the roll, pitch any yaw axis gyros respectively. These data are consistent with Long Term data; especially the erratic behavior of yaw gyro. The deviations for each 30 minute segment are graphically shown in figures 12 through 14. This data was plotted by sampling the deviation from the best fit every 36 seconds.

MINI-MIDRC DDO IRU TEST CHANNEL M1 TWX
MRY 20 TO MAY 21, 1975 RUN 055

ROLL AXIS

C-12



REFERENCE VALUE	53.700000	MEAN	
MEAN	53.734668	MEAN	
SIGMA	.05359	MEAN	
TREND	.01104	MEAN	/HOURS
SIGMA/TREND	.04582	MEAN	
AVERAGING PERIOD	71.68	SECONDS	
REJECTED POINTS	198 OUT OF 652	SAMPLES	
MINI	055M 1		

Fig 1

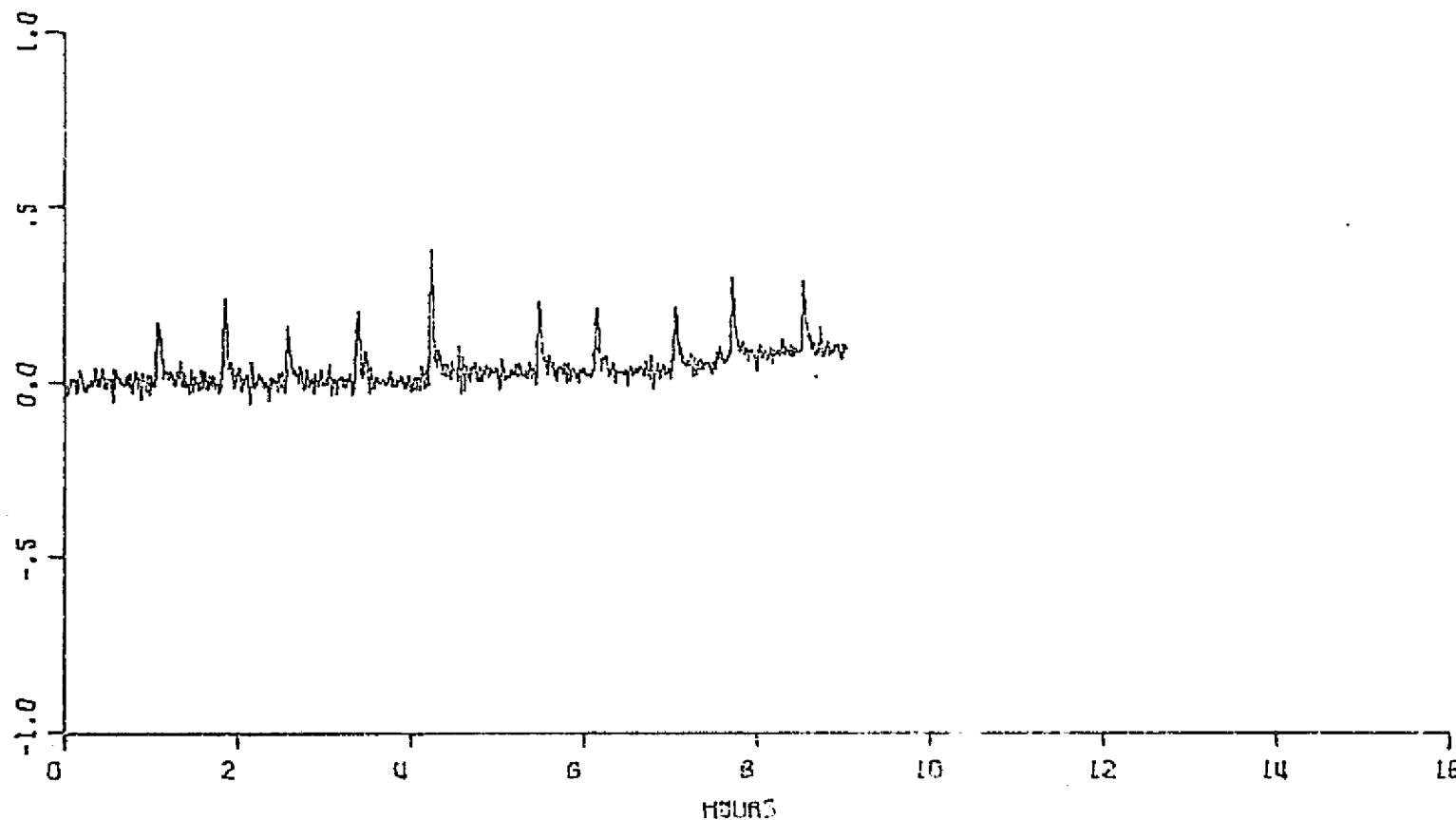
THE ABOVE DATA WERE PROCESSED BY SLIDING AN
AVERAGING 73 . 15 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
505 TEST LAB LOG 5/27/75 52

MINI-MIDRC DDO TAU TEST CHANNEL M1 TWX
MAY 20 TO MAY 21, 1975 RUN 055

ROLL AXIS



REFERENCE VALUE	53.700000	MEAU
MEAN	53.734668	MEAU
SIGMA	.05359	MEAU
TREND	.01104	MEAU /HOURS
SIGMA/TREND	.00562	PERIOD
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS	198 OUT OF 652	SAMPLES
MINI	055M L	

Fig 1

THE ABOVE DATA WERE PROCESSED BY SLIDING AN AVERAGING / 3 . 150 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

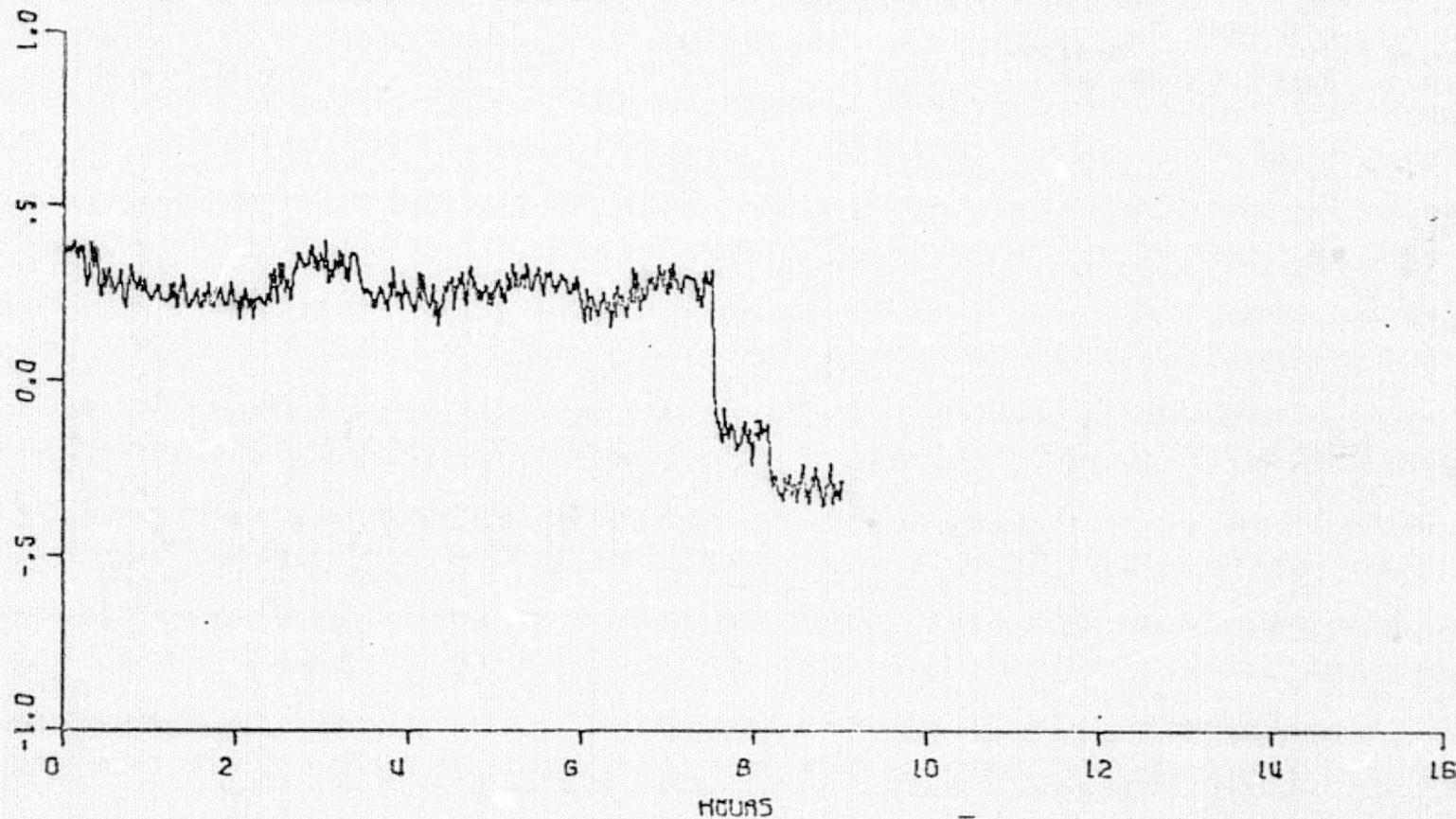
(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/REFORD FLIGHT FACILITY
515 TEST LAB CEN 9/77/75 BY

MINI-MIDC ORO IRU TEST CHANNEL M2 T/WY
MAY 20 TO MAY 21, 1975 RUN 055

PITCH AXIS

C-13



REFERENCE VALUE	-780.00000	MERU
MEAN	-779.81608	MERU
SIGMA	.1966	MERU
TREND	-.04614	MERU
SIGMA/TREND	.1545	MERU
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS	198 OUT OF 652	SAMPLES
MINNY	055M 2	

Fig 2

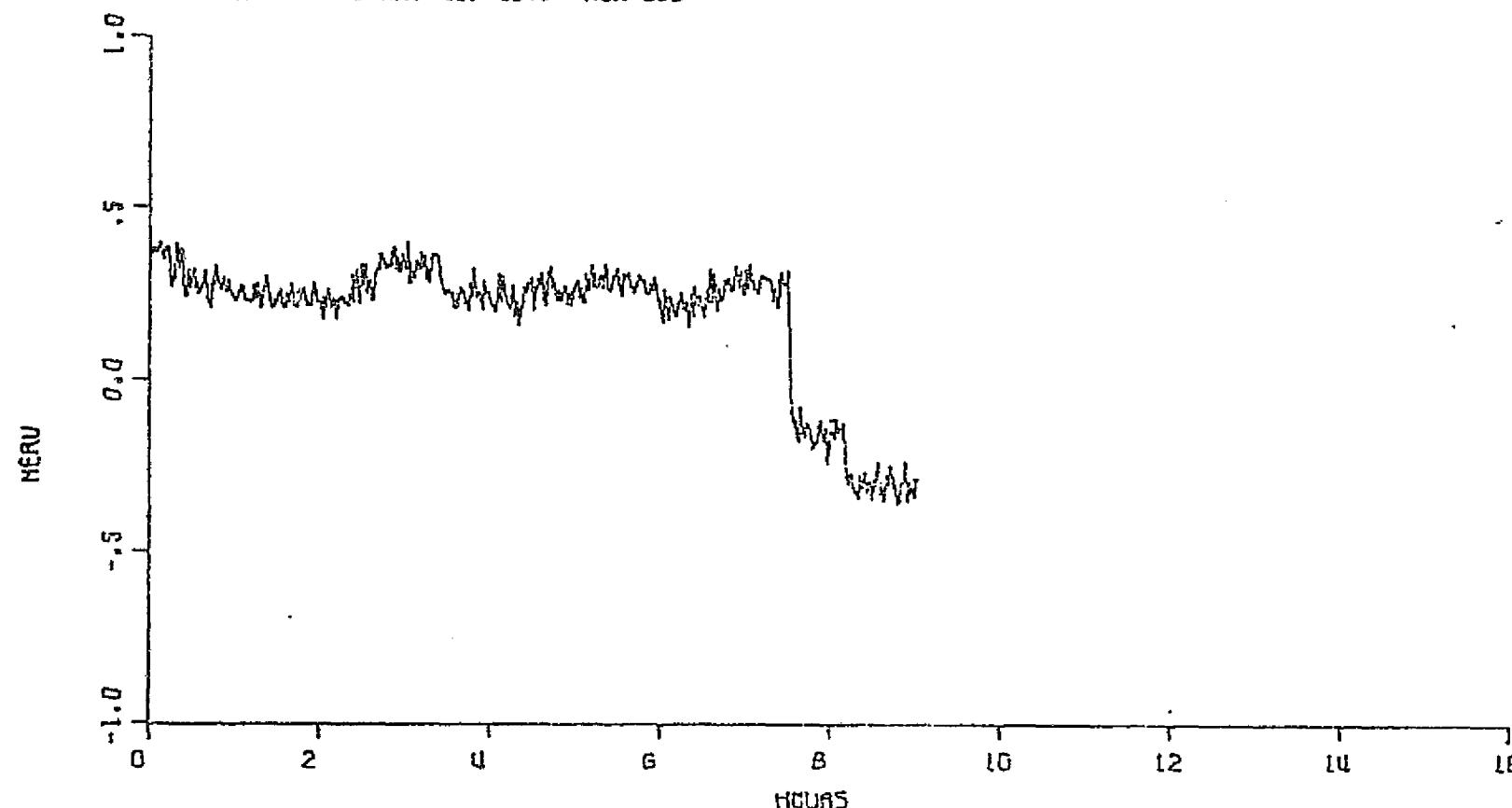
THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING .25 SEC. SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
rad's

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
SOS TEST LFB 1EX 5/27/75 6V

MINI-MIDAC GAO IMU TEST CHANNEL M2 TWA
MAY 20 TO MAY 21, 1975 RUN 055

PITCH AXIS



REFERENCE VALUE	-780.00000	MEAN	
MEAN	-779.81668	MEAN	
SIGMA	.1966	MEAN	
TREND	-.04614	MEAN	-.07135
SIGMA/TREND	.1545	MEAN	
AVERAGING PERIOD	71.68	STDEV	
REJECTED POINTS	198 OUT OF 652	STDEV	
MIN/MAX	0.55M 2	STDEV	

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING .47 .25 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

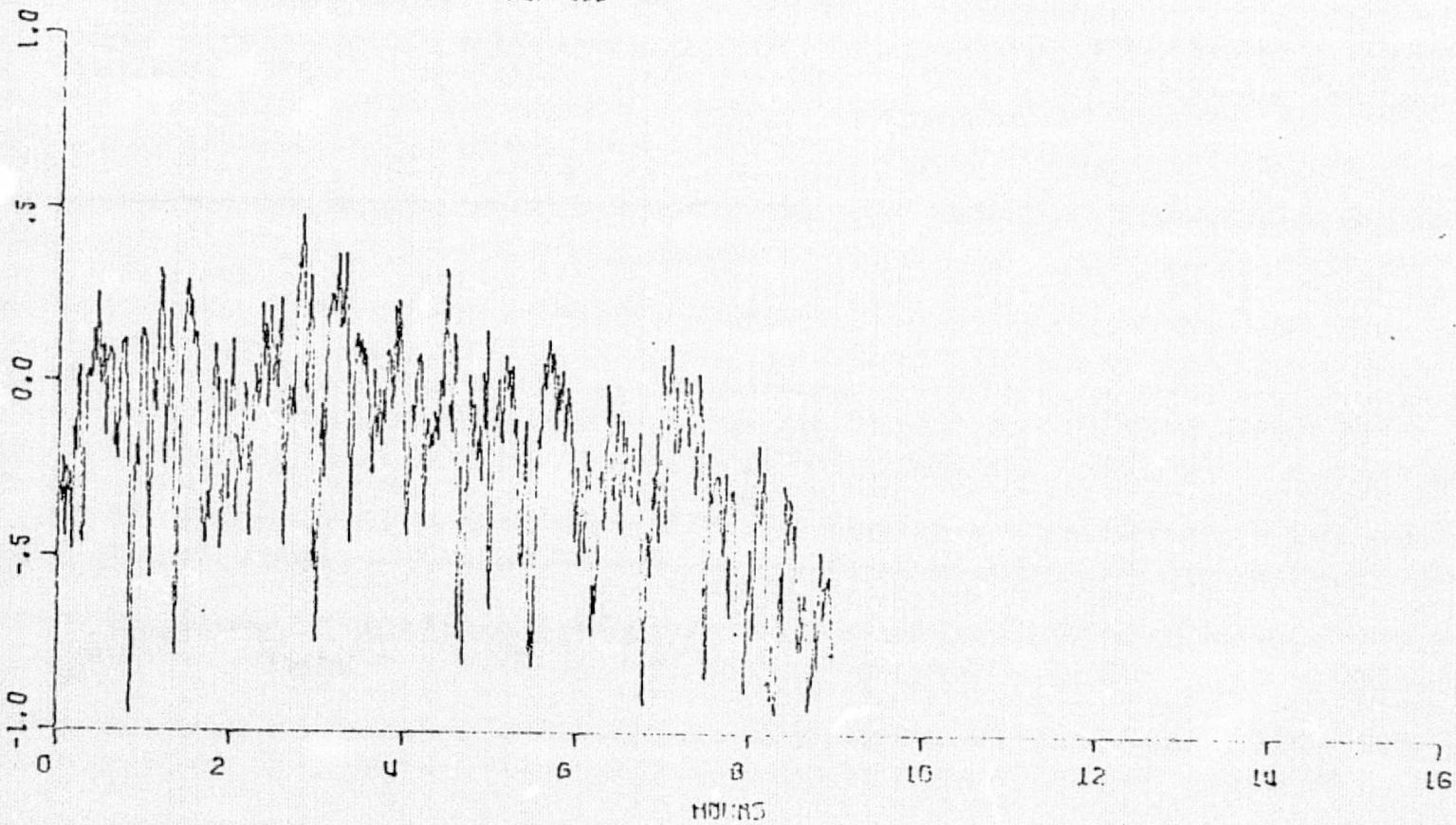
Fig. 2

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SMS TEST LFD LEX 5/27/75 8V

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MINI-MIDAC ODO IRU TEST CHANNEL M3 TWZ
MAY 20 TO MAY 21, 1975 RUN 055

YAW AXIS



REFERENCE VALUE	-718.69999	MERU
MEAN	-718.90233	MERU
SIGMA	.2899	MERU
TREND	-.05416	MERU / HOURS
SIGMA/TREND	.7541	MERU
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS	207 OUT OF 652	SAMPLES
MTHNY	OSSM 3	

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING .25 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

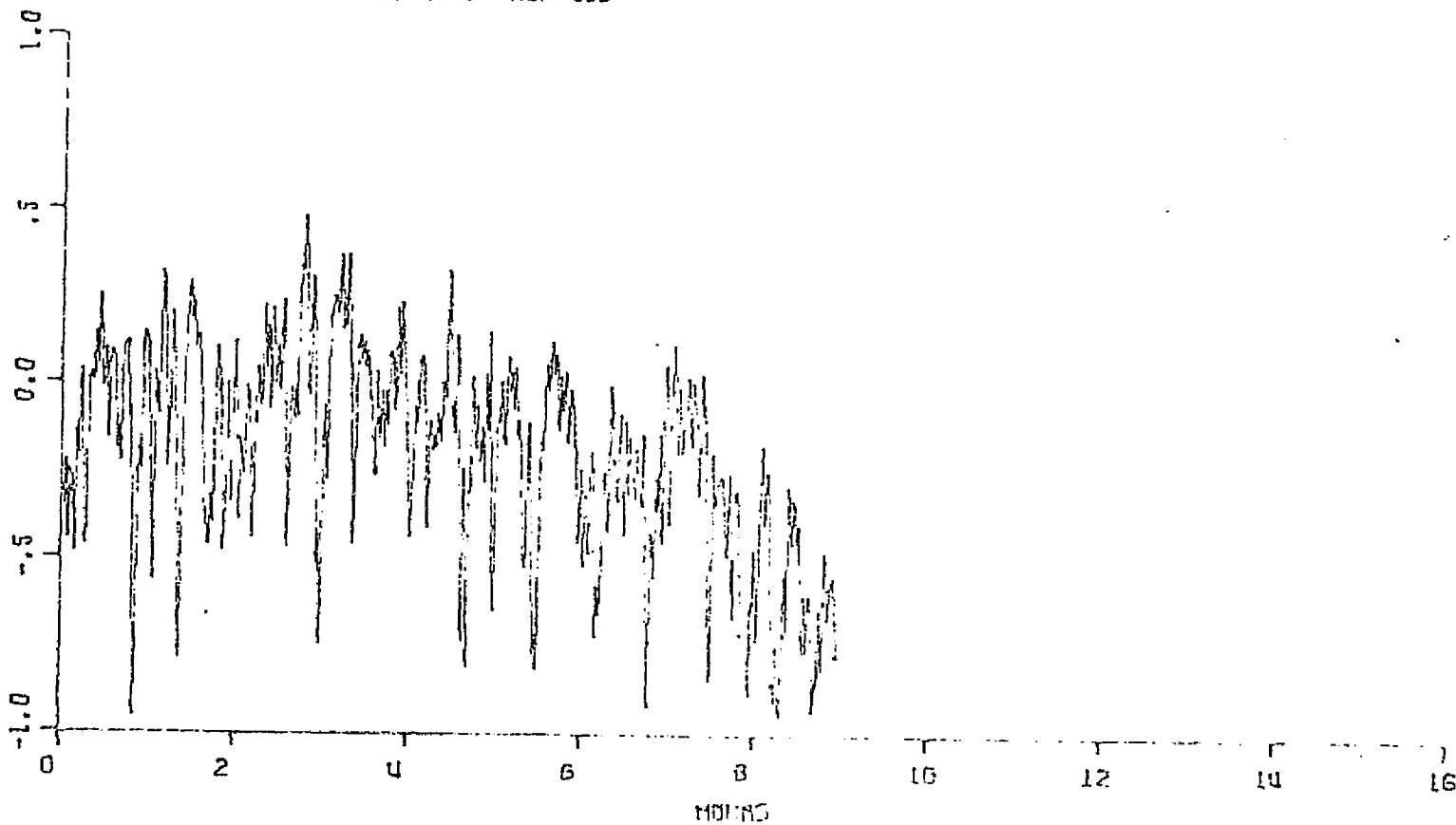
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520 TEL 1 555 3727/75 67

Fig. 3

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MINI-MIOPC GAO IAU TEST CHANNEL M3 TWZ
MAY 20 TO MAY 21, 1975 RUN 055

YAW AXIS



REFERENCE VALUE	-718.69999	MEAN
MEAN	-718.90233	MEAN
SIGMA	.2899	MEAN
TREND	-.05416	MEAN
SIGMA/TREND	.7541	MEAN
AVERAGING PERIOD	71.62	SETRNGS
REJECTED POINTS	207 OUT OF 652	SAMPLER
MINNY	055M 3	

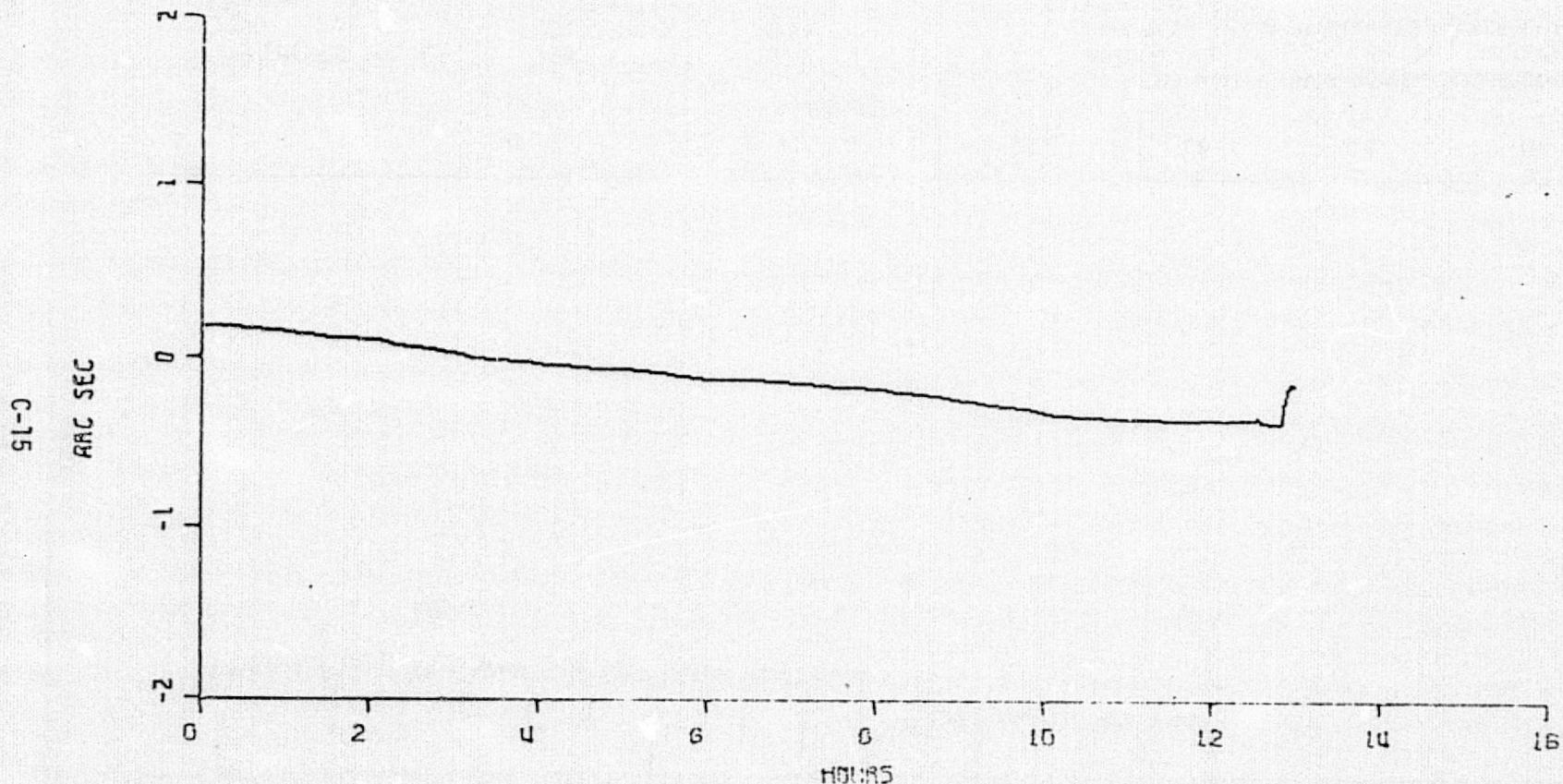
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 71.62 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/AFORD FLIGHT FACILITY
520 TEL 214 LCA 847470 8V

Fig. 3

MINI-MIDAC DDO IRU TEST CHANNEL M4 TILT METER
MAY 20 TO MAY 21, 1975 RUN 055



REFERENCE VALUE	1.8390000	ARC SEC
MEAN	1.7107270	ARC SEC
SIGMA	.1660	ARC SEC
TREND	-.04345	ARC SEC/HOURS
SIGMA/TREND	.03156	ARC SEC
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS 0	OUT OF 552	SAMPLES
MINNY 055M 4		

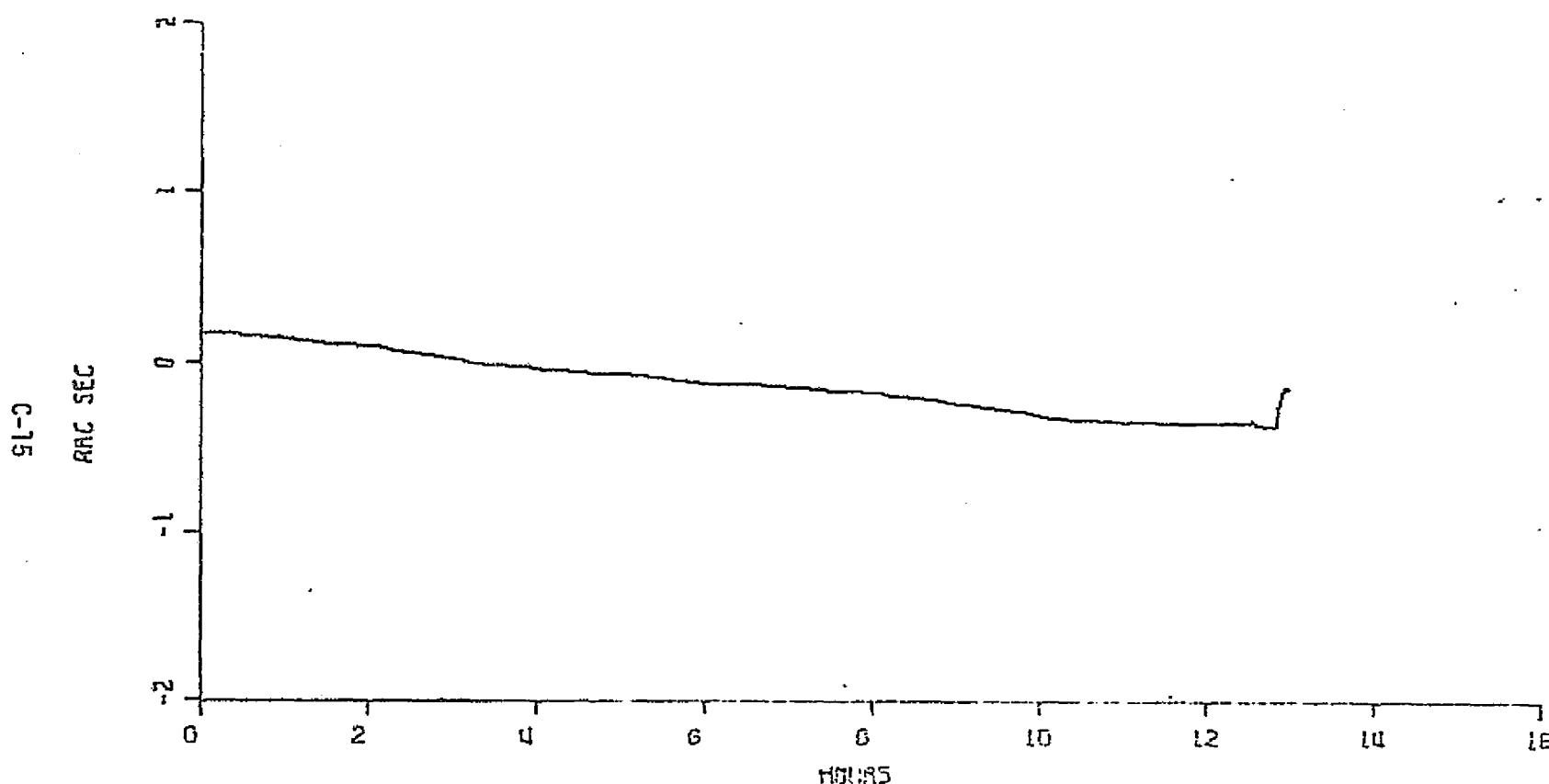
Fig. 4

THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 71.68 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
505 TEST LNS LPK 5/27/75 27

MINI-MIOPC ORO IRU TEST CHANNEL MU TILT METEOR
MAY 20 TO MAY 21, 1975 RUN 055



REFERENCE VALUE	1.8396000	ARC SEC
MEAN	1.7107270	ARC SEC
SIGMA	.1650	ARC SEC
TREND	-.00345	ARC SEC / MONTH
SIGMA/TREND	.03156	ARC SEC
HIGHGNG PERIOD	71.63	SECONDS
SELECTED POINTS 0	OUT OF 652	COUNTED
MINNY ASSM 4		

THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 100 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth

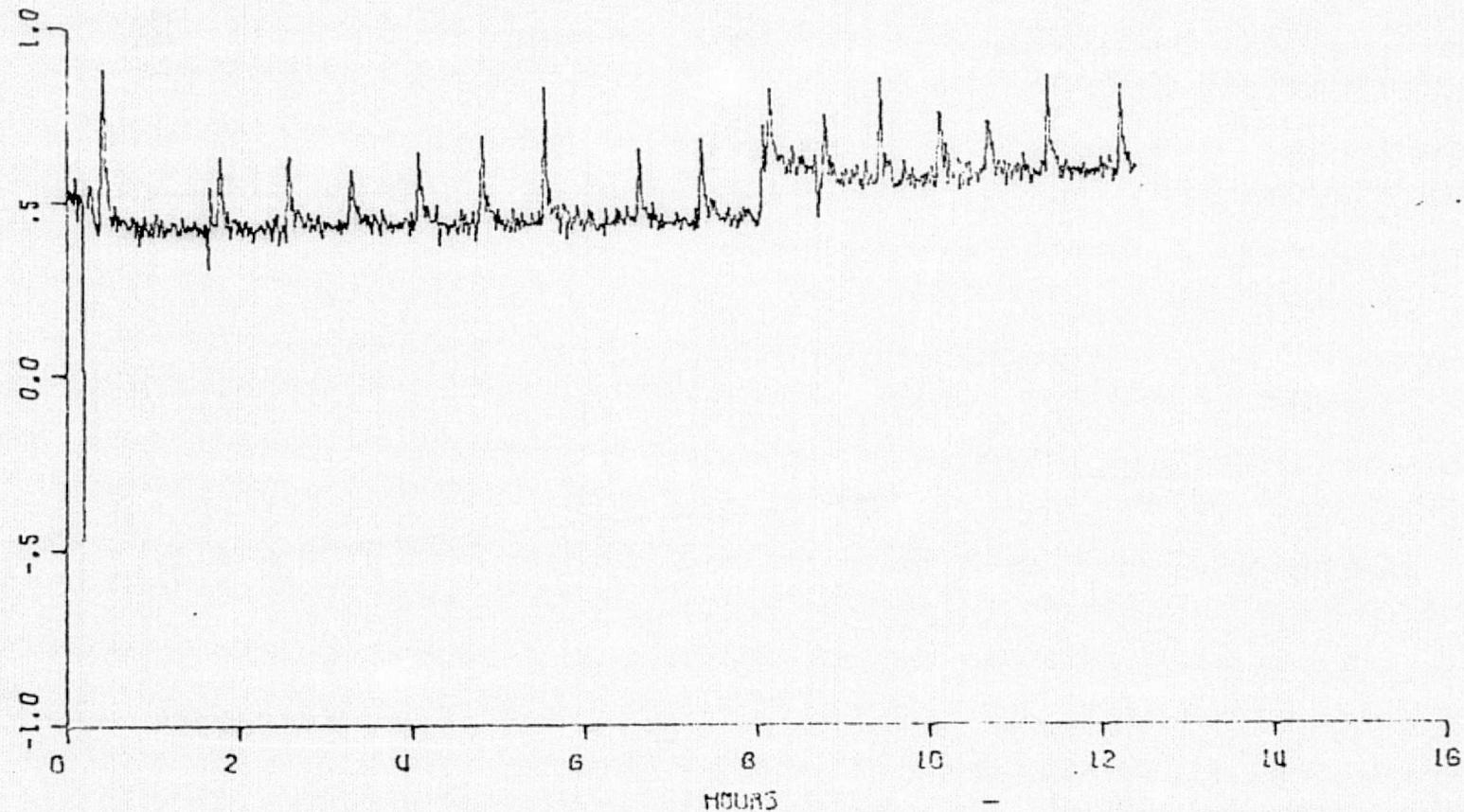
SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

1

MINI-MIDRC DDO IRU TEST CHANNEL M1 TWT
MAY 21 TO MAY 22, 1975 RUN 056

ROLL AXIS

C-16



REFERENCE VALUE	53.700000	HERU
MEAN	54.200475	HERU
SIGMA	.09771	HERU
TREND	.01735	HERU / HOURS
SIGMA/TREND	.07545	HERU
AVERAGING PERIOD	71.68	SECPHS
REJECTED POINTS	1	SAMPLES
MENNY	056M	

Fig. 5

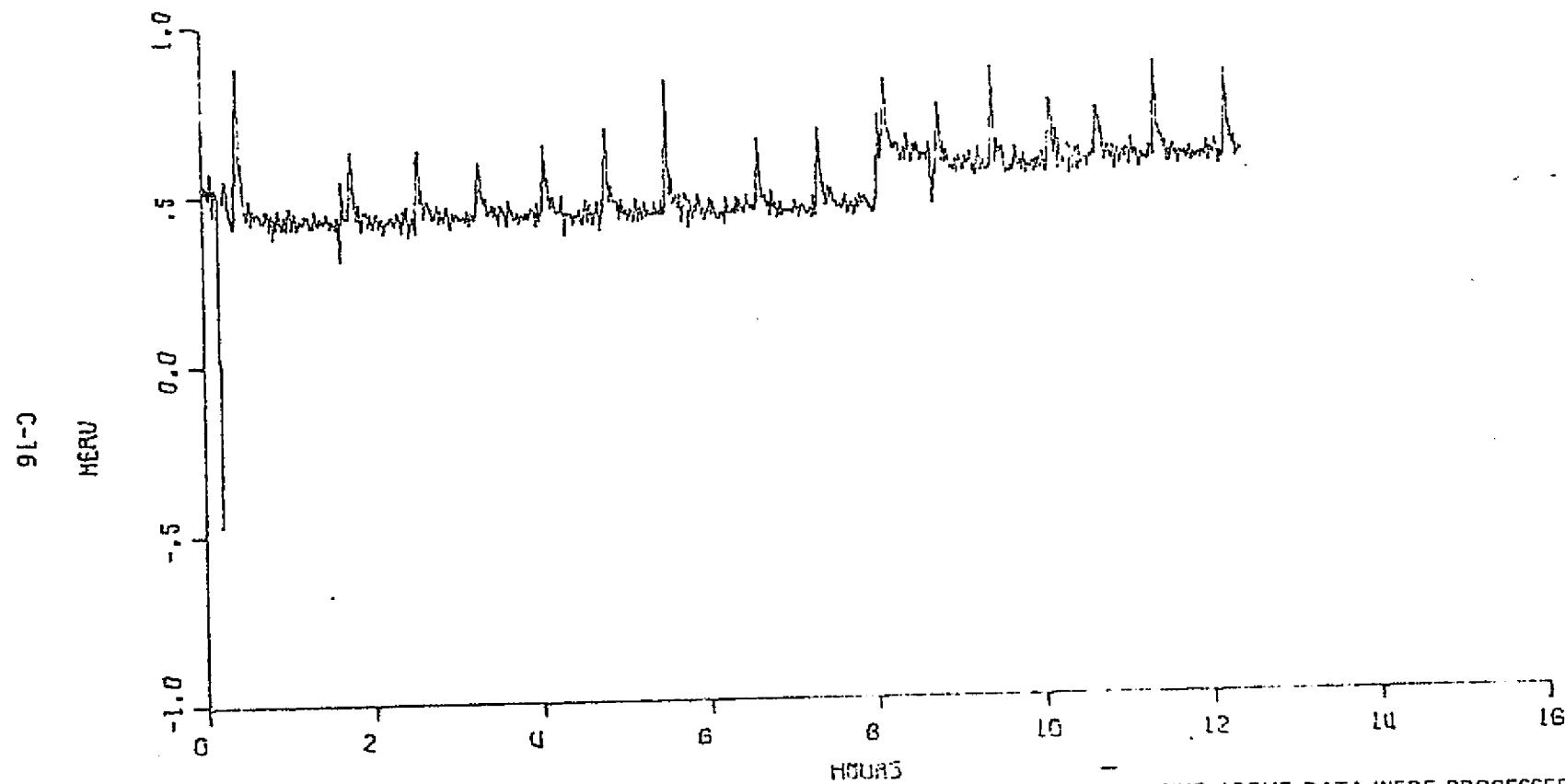
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 256 1/2 SEC CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
SSC TEST L23 10K 5/27/75 SW

MINI-MICRO DRG IRU TEST CHANNEL M1 TNY
MAY 21 TO MAY 22, 1975 RUN 056

ROLL AXIS



REFERENCE VALUE	53.760000	MEAN
MEAN	54.250475	MEAN
SIGMA	.09771	MEAN
TREND	.01735	MEAN / HOURS
SIGMA/TREND	.07543	MEAN
AVERAGING PERIOD	71.68	SAMPLES
REJECTED POINTS	1	SAMPLES
MINNY	556M	

Fig. 5

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 25.125 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

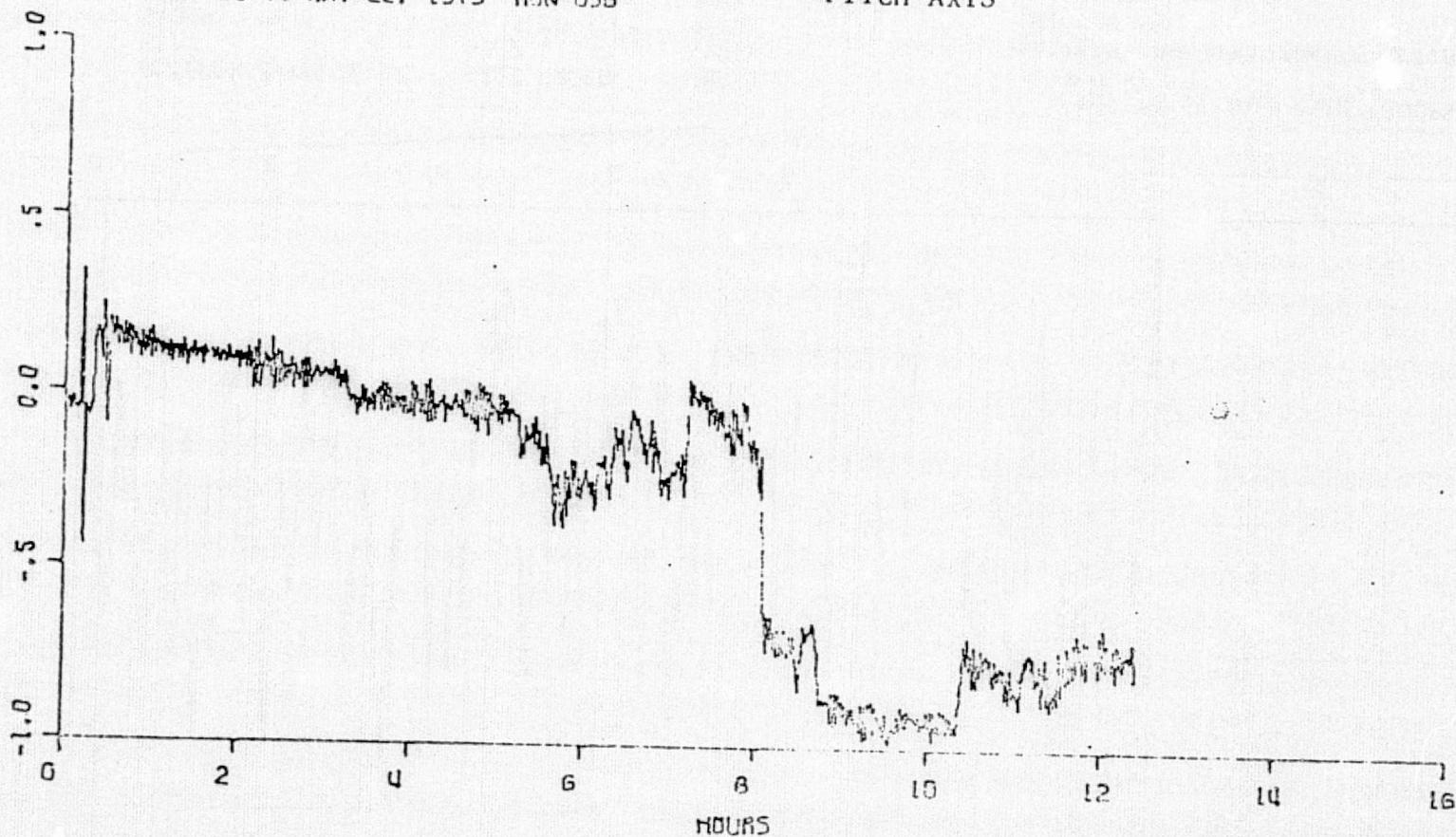
(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
END TEST 12:00 PM 27/7/75 BY

MINI-MIFORC DRO IRU TEST CHANNEL M2 TWT
MAY 21 TO MAY 22, 1975 RUN 056

PITCH AXIS

C-17



REFERENCE VALUE	-781.00000	MEGU
MEAN	-781.30637	MEGU
SIGMA	.3892	MEGU
TREND	-.09595	MEGU . HOURS
SIGMA/TREND	.1031	MEGU
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS	2 OUT OF 523	SAMPLES
MINNY	056M 2	

Fig. 6

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 28 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

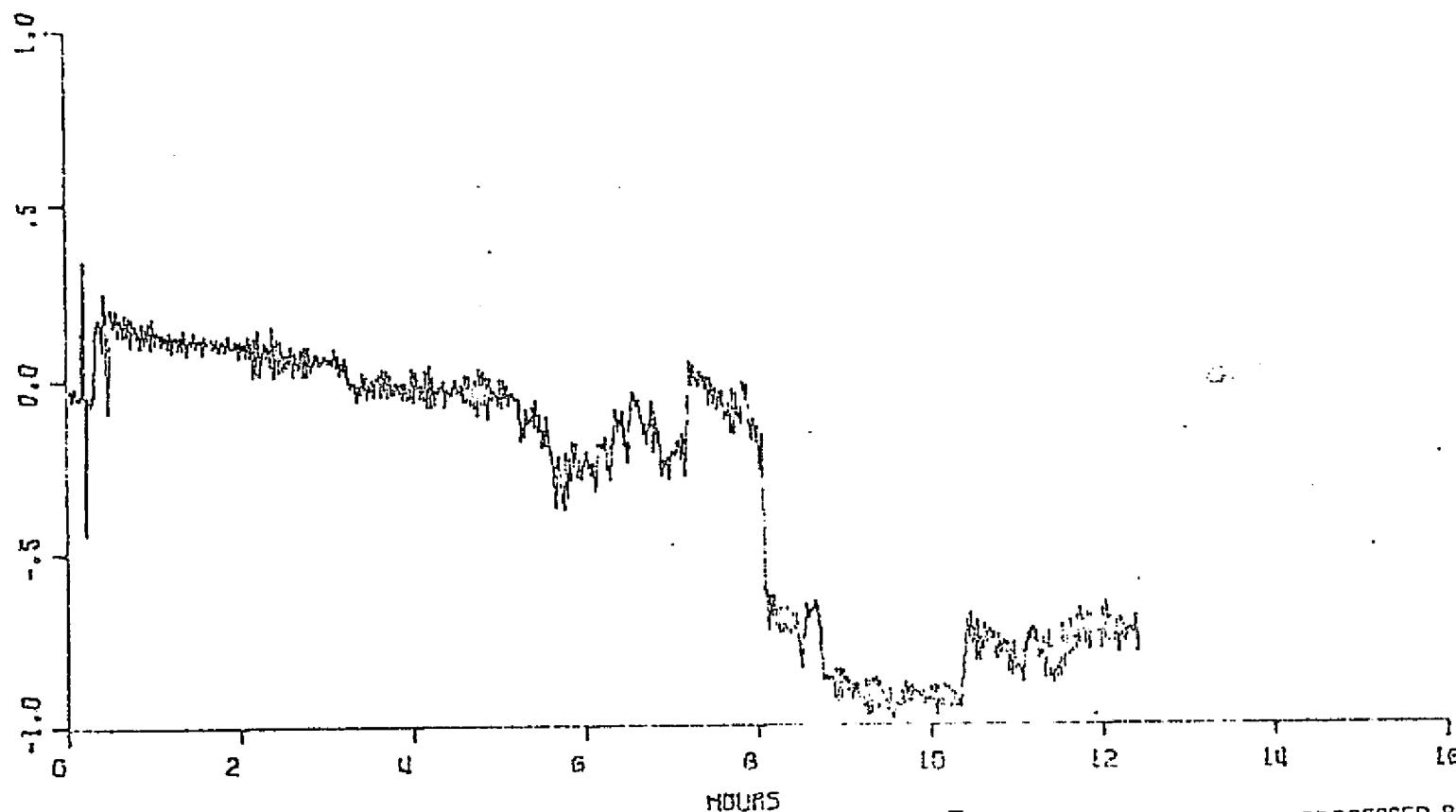
SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

ENG TEST LPG 15K 5V 7700 8V

MINI-MIDRC DSD IRU TEST CHANNEL M2 TWT
MAY 21 TO MAY 22, 1975 RUN 056

PITCH AXIS

C-17



REFERENCE VALUE	-781.00000	MEAN
MEAN	-781.30637	MEAN
SIGMA	.3892	MEAN
TREND	-.09595	MEAN . HOURS
SIGMA/TREND	.1031	MEAN
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS	2	SAMPLES
MINNY	05GM	2

Fig. 6

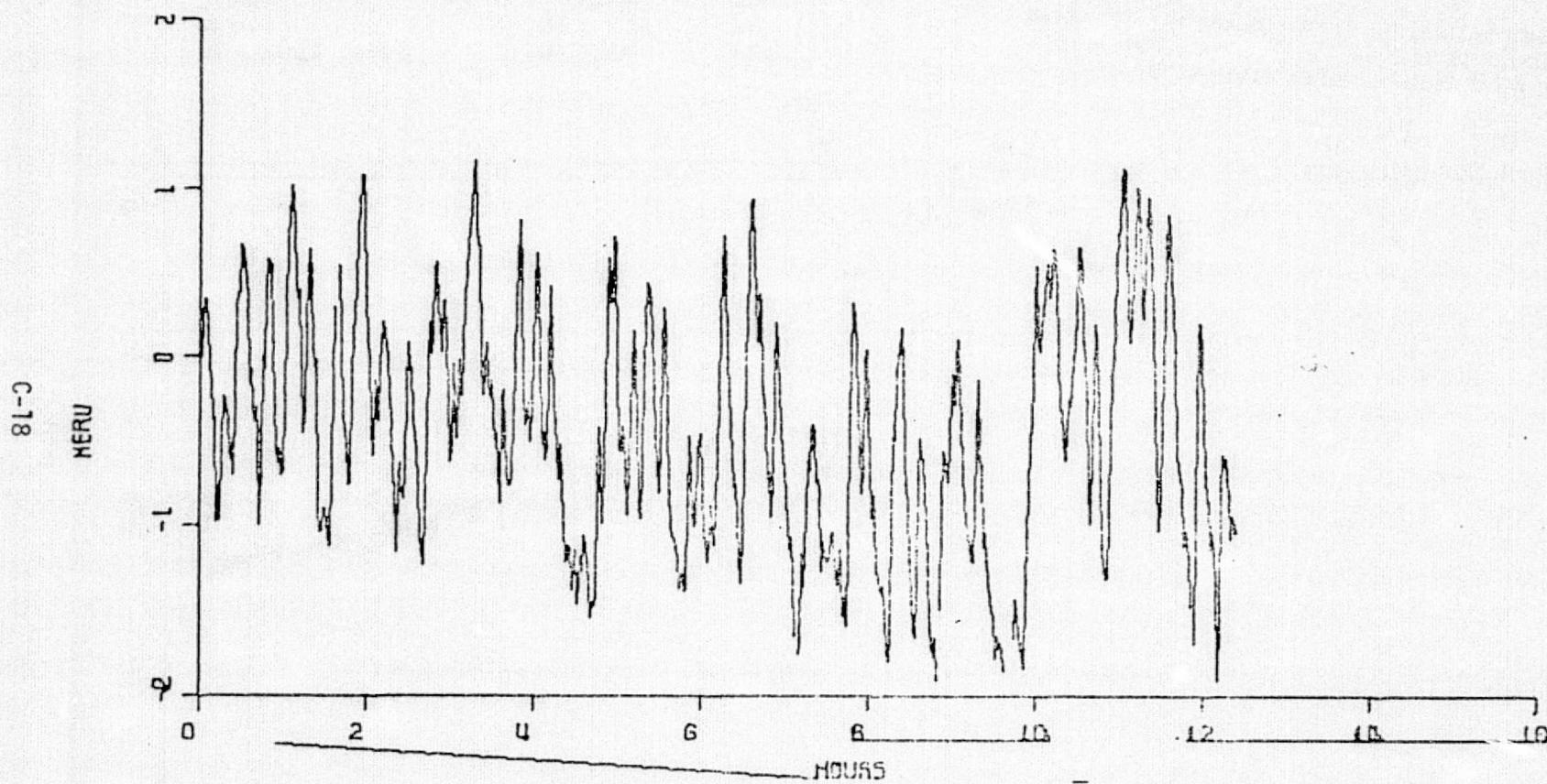
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 71.68 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
DSD TEST ENG 17K 5/27/75 BY

MINI-MIDRC DDO IRU TEST CHANNEL M3 THZ
MAY 21 TO MAY 22, 1975 RUN 056

YAW AXIS



REFERENCE VALUE	-720.02020
MEAN	-720.41500
STOIA	.6661
TREND	-.00740
SIGMA/TREND	.8222
AVERAGE TIME PERIOD	71.68
NUMBER OF POINTS	10
MINNY	0568 3
MAXNY	0569 3

MERU	/HOURS
MERU	
MERU	
MERU	
SECONDS	
SHUTLE	

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 7/8 , 1/4, 1/4 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

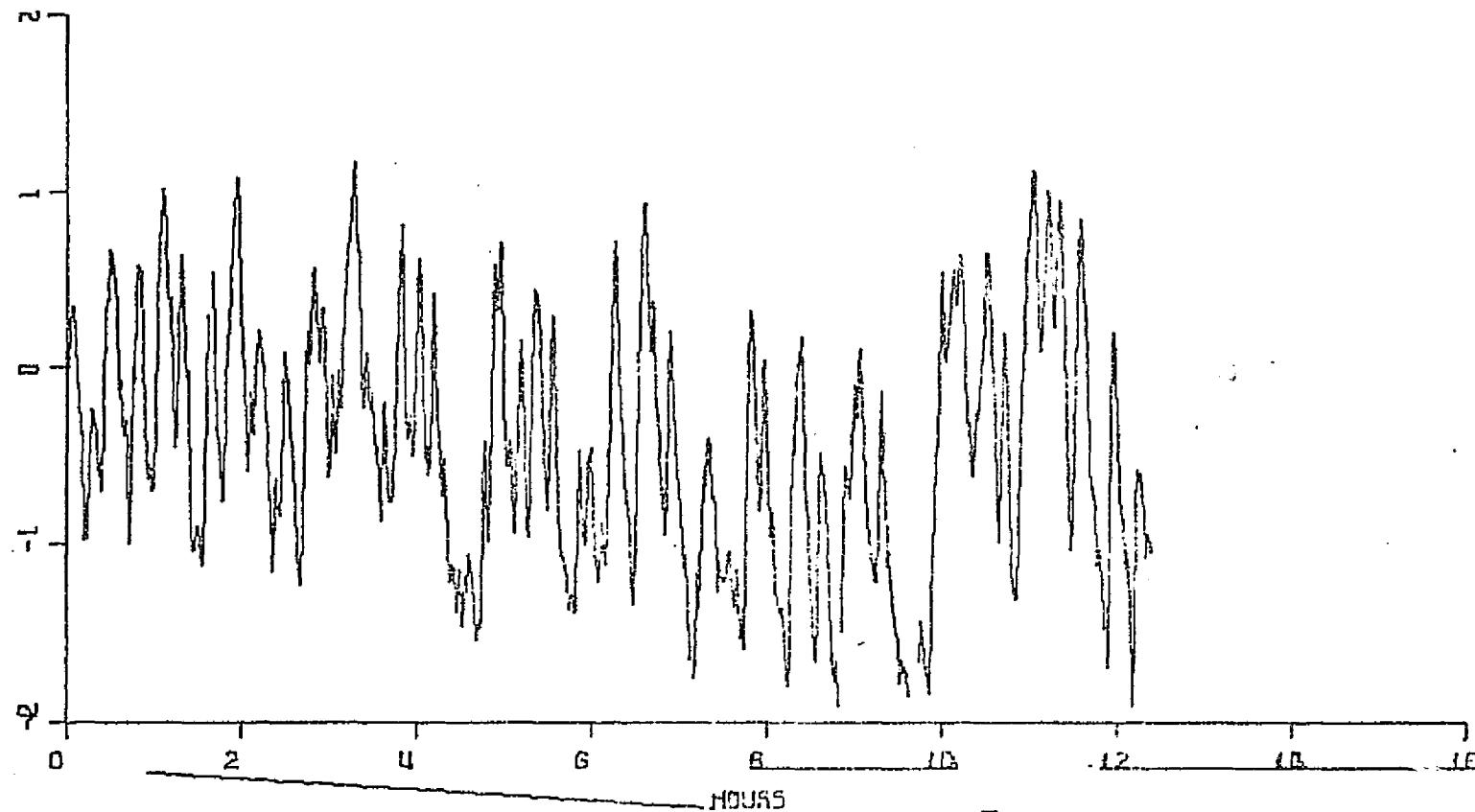
SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
SCS TEST LAB LPK 5/27/75 BY

Fig. 7

MINI-MIDAC DRC IRU TEST CHANNEL M3 THZ
MAY 21 TO MAY 22, 1975 RUN 056

YAW AXIS

C-18



REFERENCE VALUE	-720.00000	MERU
MEAN	-720.41500	MERU
STDRA	.6861	MERU
TREND	-.07740	/HOURS
B100/TREND	.6209	MERU
ACQUISITION PERIOD	71.18	SECONDS
NUMBER OF POINTS	10	SAMPLES
MINNY	0568 3	

Fig. 7

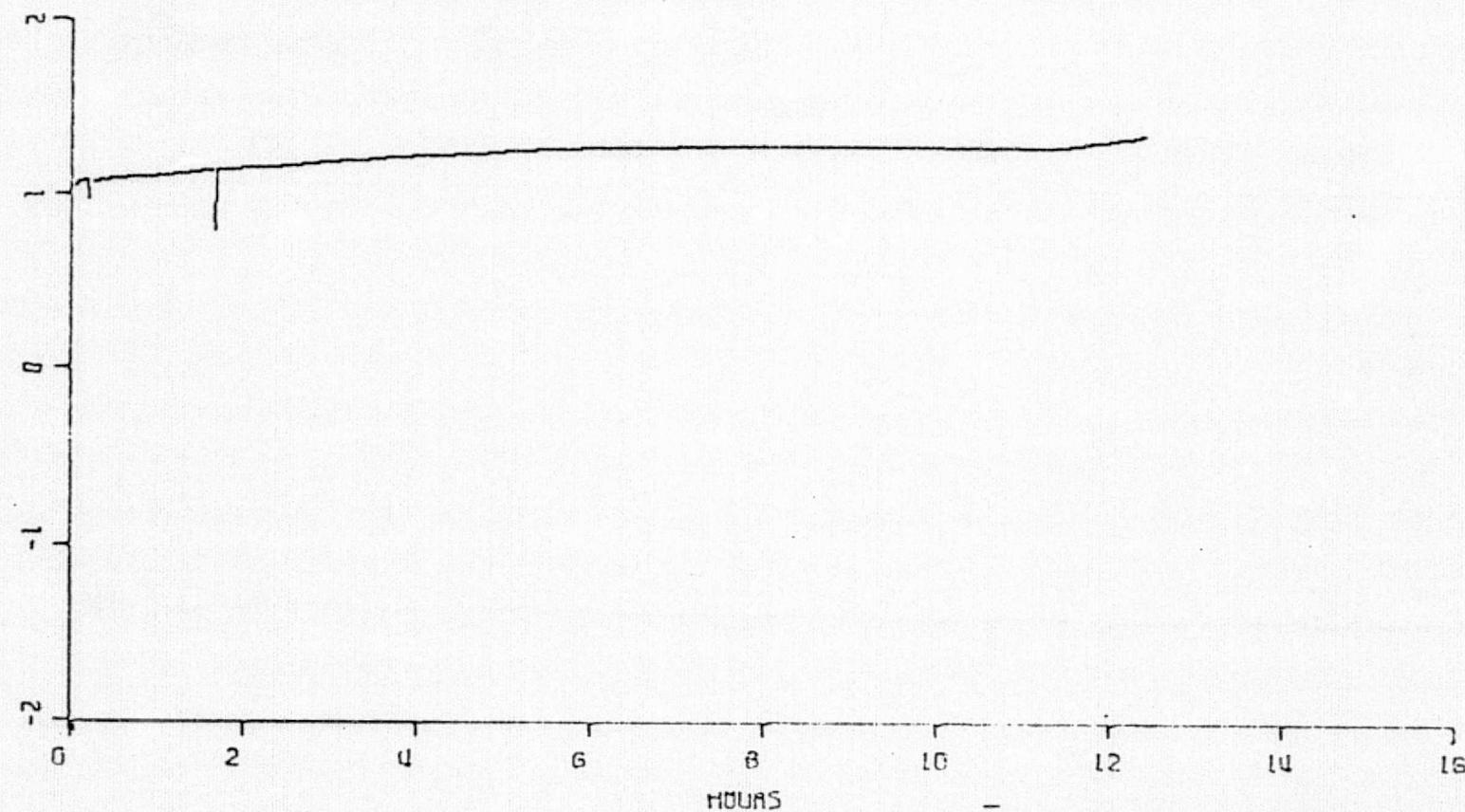
THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 200 1/2, 1/4 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
505 TEST LAB LFC 3/27/75 BY

MINI-MIDRC OAO IRU TEST CHANNEL M4 TILT METER
MAY 21 TO MAY 22, 1975 RUN 056

C-19



REFERENCE VALUE	1.0390000	ARC SEC
MEAN	3.0783632	ARC SEC
SIGMA	.07254	ARC SEC
TREND	.01796	ARC SEC/HOURS
SIGMA/TREND	.03369	ARC SEC
AVERAGING PERIOD	71.68	SECONDS
REJECTED POINTS ?	OUT OF 623	SAMPLES
MINNY	056M 4	

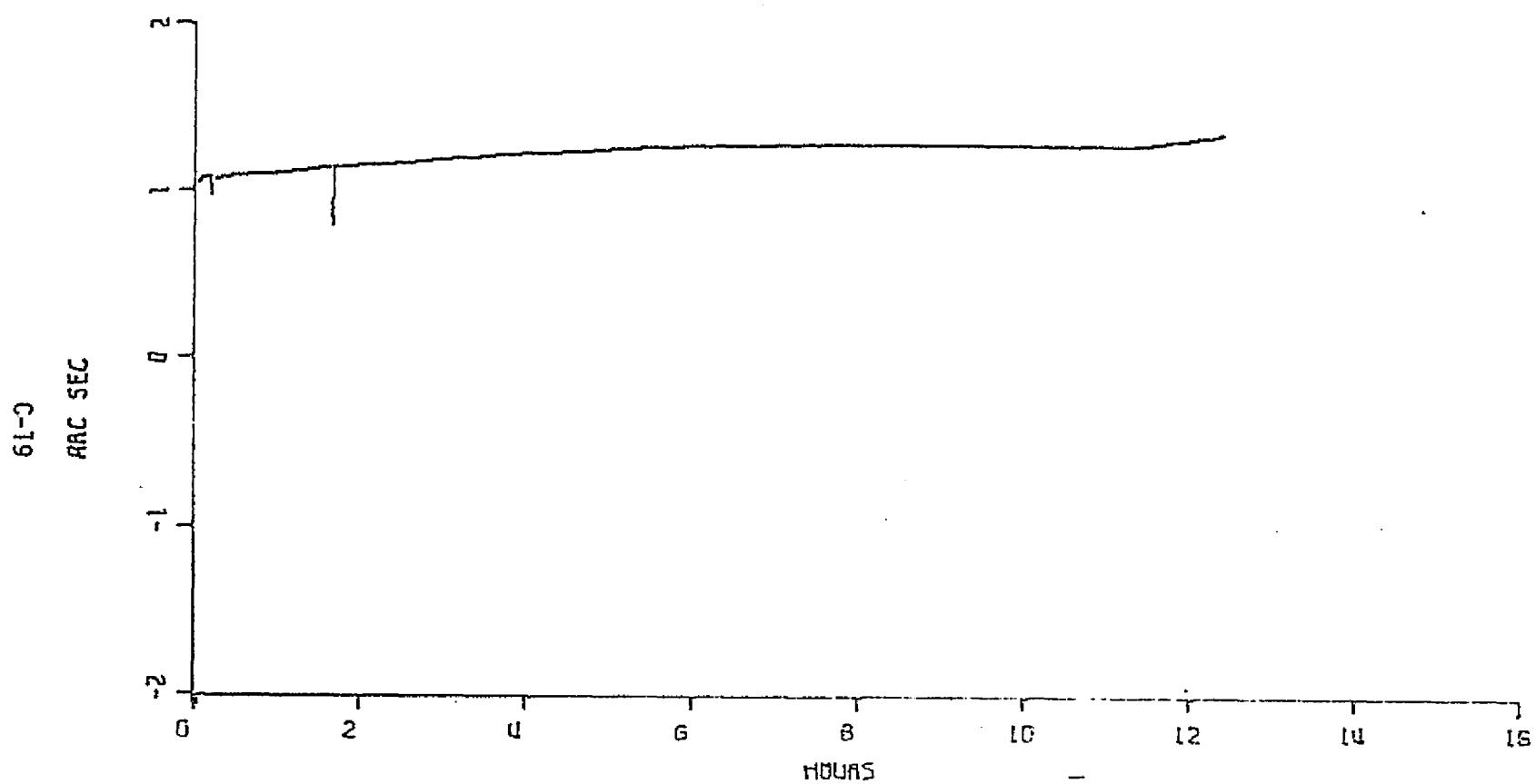
THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 25 1/2 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY
END TEST LFB 158 077775 67

Fig. 8

MINI-MIDRC GAO IRU TEST CHANNEL M4 TILT METER
MAY 21 TO MAY 22, 1975 RUN 056



REFERENCE VALUE	1.0390000	ARC SEC
MEAN	3.0783632	ARC SEC
SIGMA	.07254	ARC SEC
TREND	.01796	ARC SEC/HOURS
SIGMA/TREND	.03369	ARC SEC
AVERAGING PERIOD	71.63	SECONDS
REJECTED POINTS ?	OUT OF 623	SAMPLES
MINNY	056M 4	

THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 25 .45 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

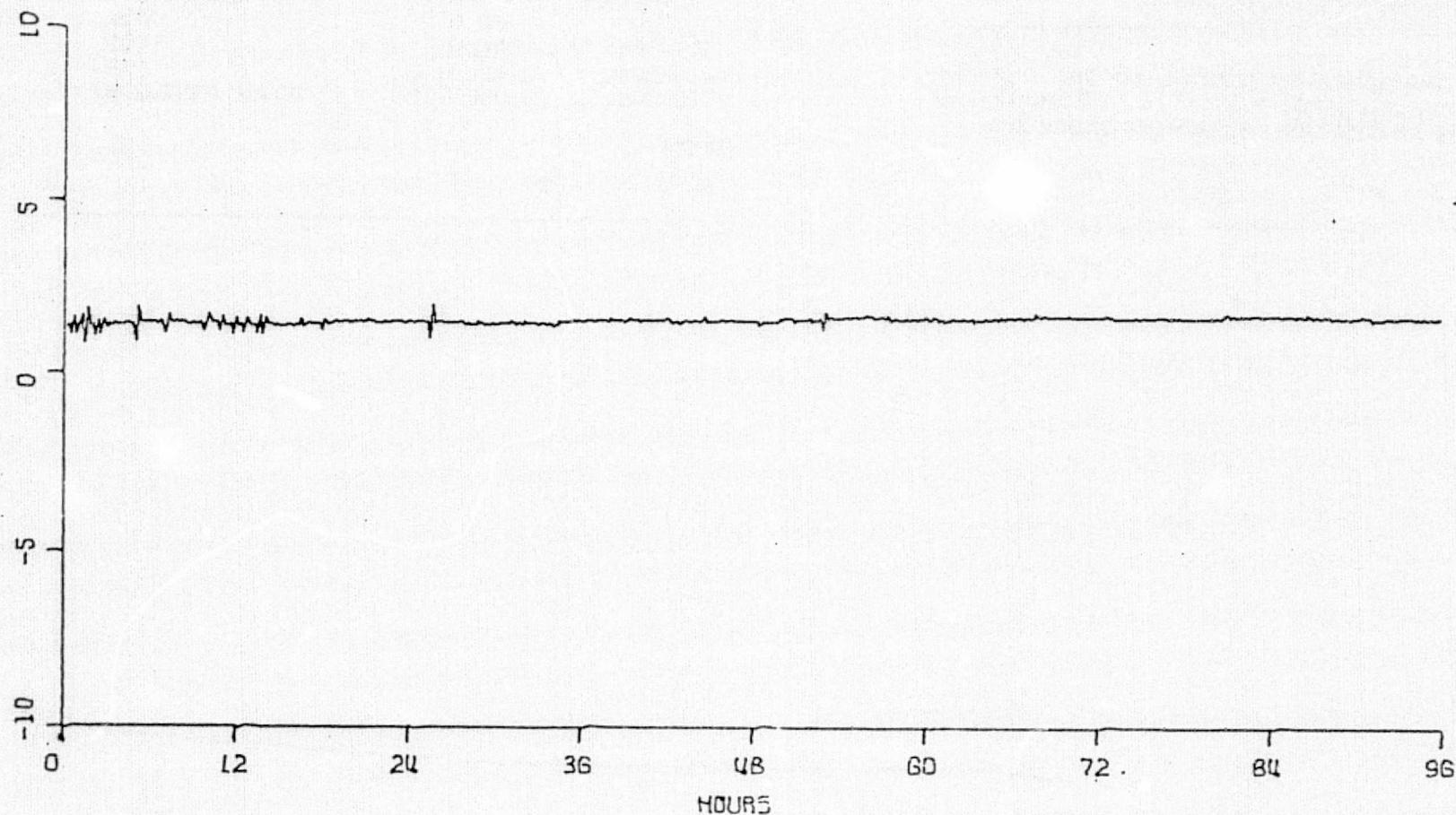
DATA PLOT AND RUN 056, MAY 22, 1975

Fig. 8

MINI-NICRO CHANNEL MI TRX OAD-IRU TEST 20.48 SEC/SAMPLES
MAY 22 TO MAY 28, 1975 GSFC RUN 059

ROLL AXIS

C-26



REFERENCE VALUE	53.000000	MERU
MEAN	54.537159	MERU
SIGMA	.1271	MERU
TREND	.003274	MERU /HOURS
SIGMA/TREND	.09901	MERU
AVERAGING PERIOD	675.84	SECONDS
REJECTED POINTS 0	OUT OF 511	SAMPLES
MINNY 059M L		

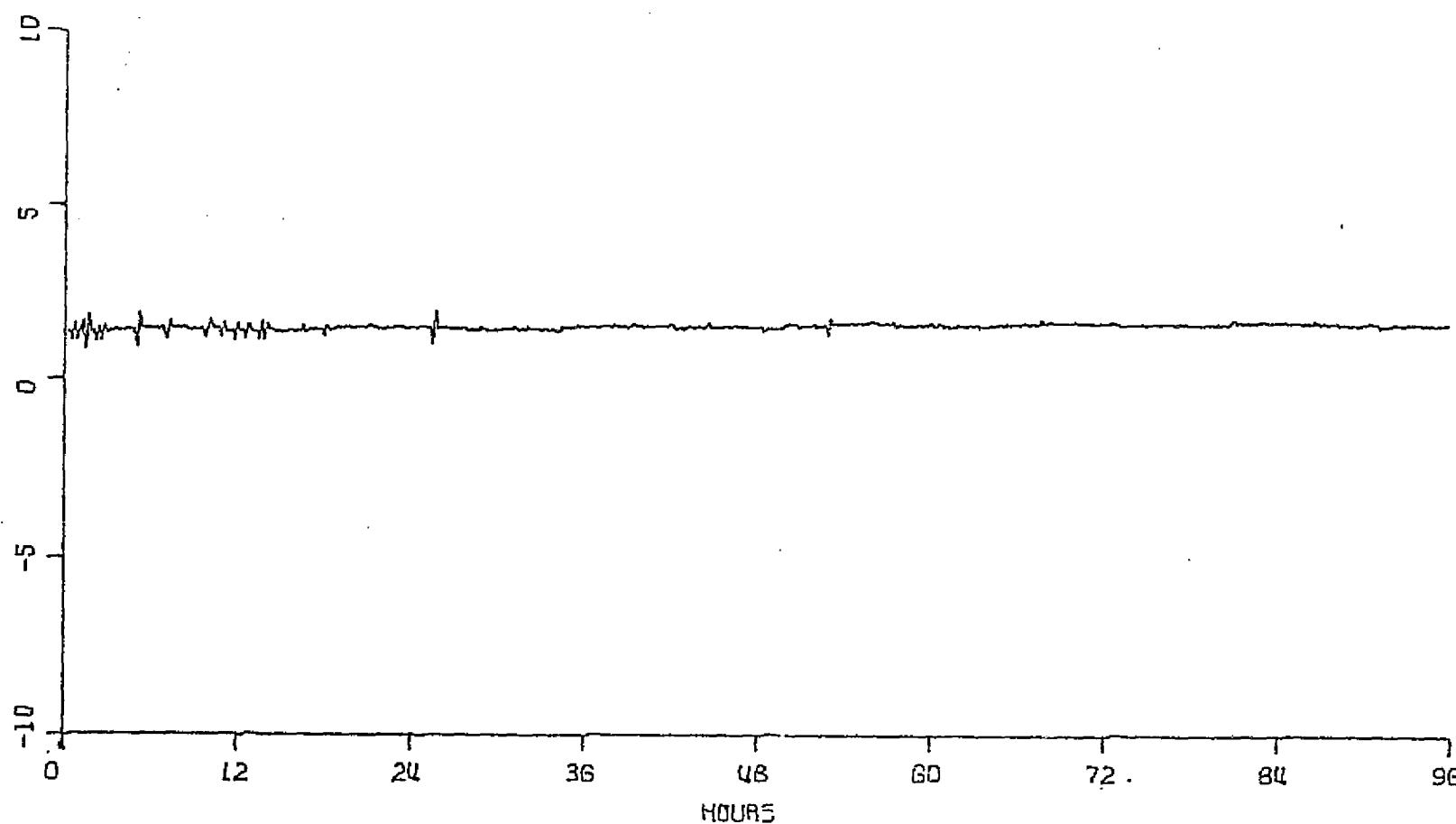
Fig 9

SOS TEST LAB 15K 6/4/75 BV

MINI-MICRO CHANNEL M1 TWR DAD-IRU TEST 20.48 SEC/SAMPLES
MAY 22 TO MAY 28, 1975 GSFC RUN 059

ROLL AXIS

C-26



REFERENCE VALUE	53.000000	MERU
MEAN	54.537159	MERU
SIGMA	.1271	MERU
TREND	.003274	MERU /HOURS
SIGMA/TREND	.09301	MERU
AVERAGING PERIOD	675.84	SECONDS
REJECTED POINTS	0 OUT OF 511	SAMPLES
MIN/MAX	059M 1	

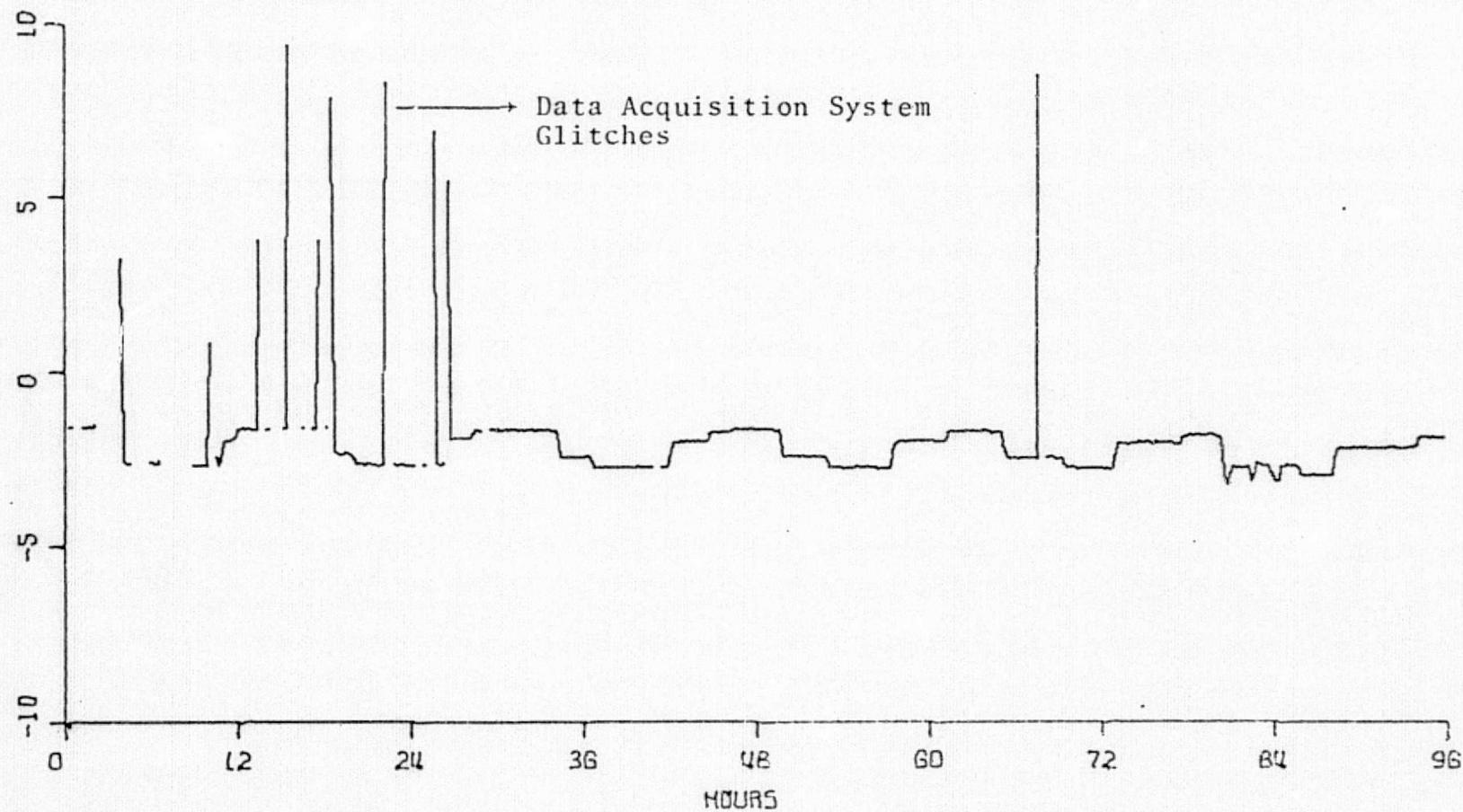
Fig 9

S05 TEST LAB L5K 6/4/75 BV

MINI-MIDAC CHANNEL M2 TWT OAD-TRU TEST 20.48 SEC/SAMPLES
MAY 22 TO MAY 28, 1975 GSFC RUN 059

PITCH AXIS

C-21

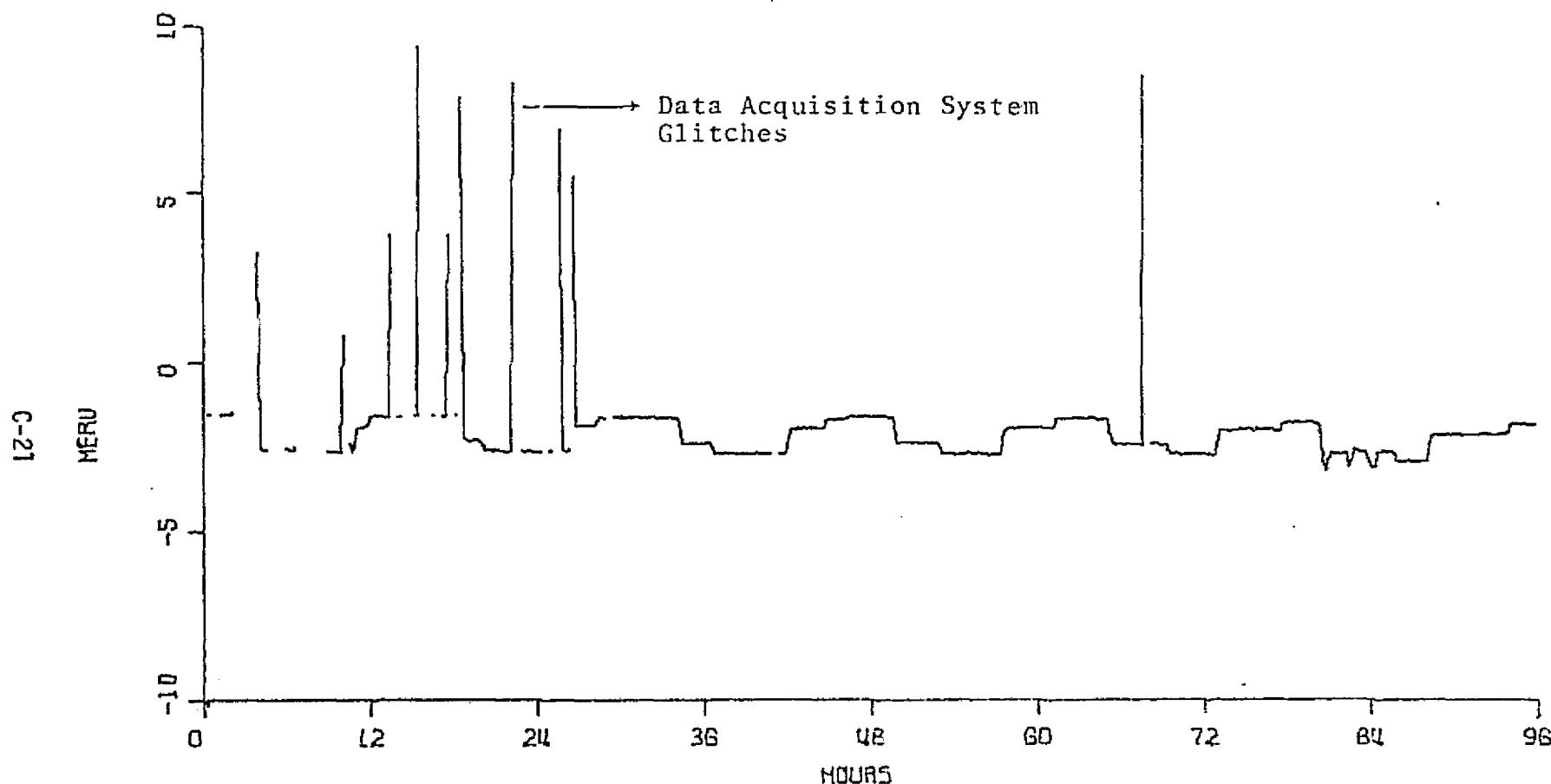


REFERENCE VALUE	-780.00000	MERU
MEAN	-782.00962	MERU
SIGMA	1.6393	MERU
TREND	-0.0613	MERU /HOURS
SIGMA/TREND	1.5828	MERU
AVERAGING PERIOD	675.84	SECONDS
REJECTED POINTS	49 OUT OF 511	SAMPLES
MINNY	059M 2	

Fig 10

MINT-MIDAC CHANNEL M2 TWT OAD-TRU TEST 20.48 SEC/SAMPLES
MAY 22 TO MAY 28, 1975 GSFC RUN 059

PITCH AXIS



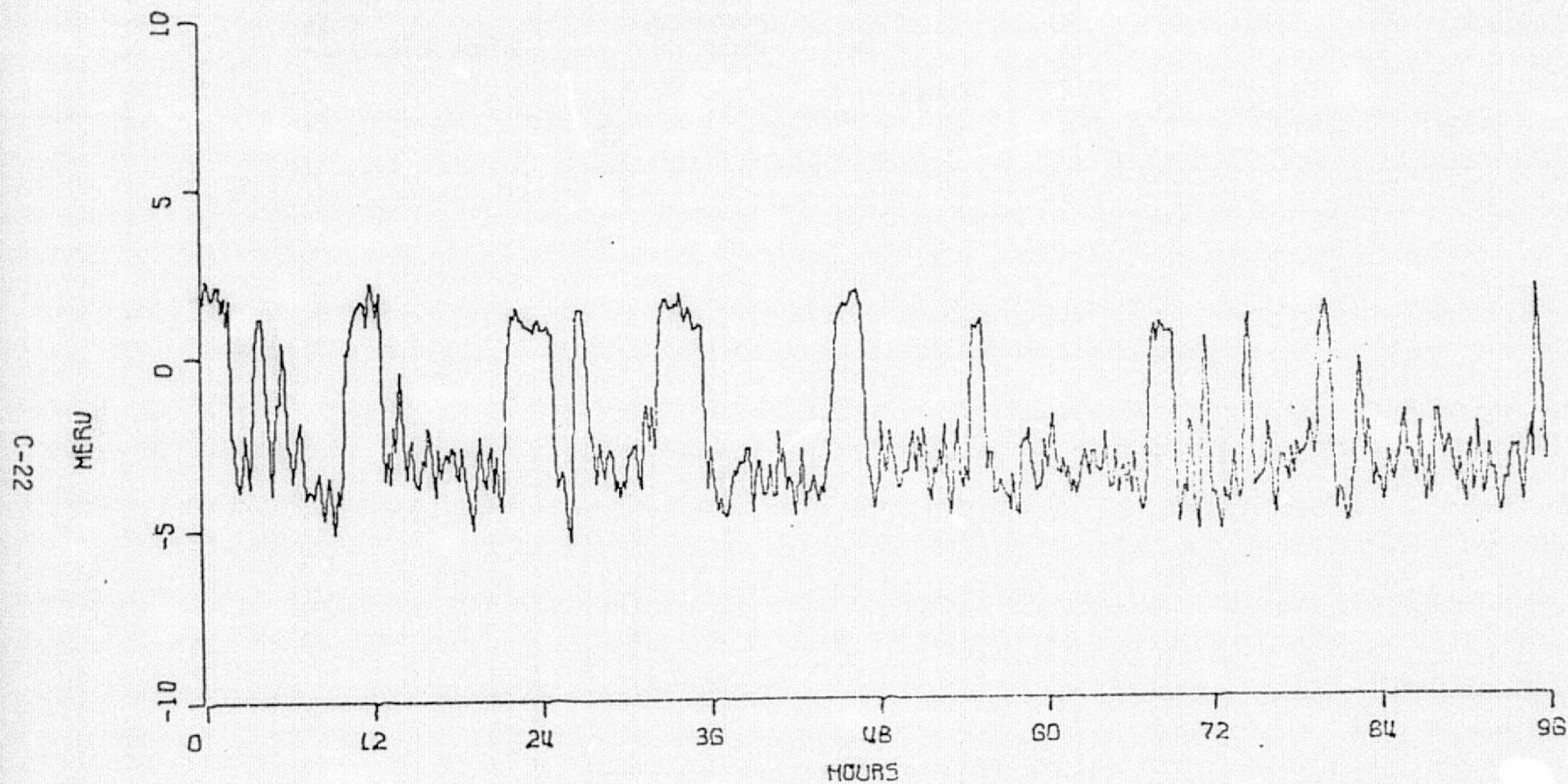
REFERENCE VALUE	-780.00000	MERO
MEAN	-782.00962	MERO
SIGMA	1.6393	MERO
TREND	-.01613	MERO / HOURS
SIGMA/TREND	1.5828	MERO
AVERAGING PERIOD	675.84	SECONDS
REJECTED POINTS	49 OUT OF 511	SAMPLES
MINNY	059M 2	

Fig. 10

585 TEST LAB LSK 5/4/75 BY

MINI-MIDRC CHANNEL M3 TWO-DIM-TRU TEST 20.48 SEC/SAMPLES
MAY 22 TO MAY 28, 1975 GSFC RUN 059

YAW AXIS



REFERENCE VALUE	-720.00000	MERU
MEAN	-722.35223	MERU
SIGMA	1.9524	MERU
TREND	-.01894	MERU /HOURS
SIGMA/TREND	1.6605	MERU
AVERAGING PERIOD	675.84	HOURS
REJECTED POINTS	0 OUT OF 511	SAMPLES
MINNY	059M 3	

Fig 11

SOS TEST LAB L5K 6/4/75 5V

GYRO	RUN	NUMBER	SEGMENT	TIME (MINUTES)	TREND (MERU)	RESIDUE (ARCSEC)		
			POINT COUNT			MAX	MIN	SIGMA
ROL	054	1	9210	30.720	53.696	0.307	-0.455	0.102
ROL	054	2	9210	30.720	53.685	0.411	-0.386	0.117
ROL	054	3	9210	30.720	53.719	0.726	-0.415	0.178
ROL	054	4	9210	30.720	53.708	0.462	-0.683	0.135
ROL	054	5	9210	30.720	53.702	0.356	-0.440	0.113
ROL	054	6	9210	30.720	53.702	0.636	-0.467	0.141
ROL	054	7	9210	30.720	53.725	0.494	-0.574	0.155
ROL	054	8	9210	30.720	53.685	0.549	-0.396	0.120
ROL	054	9	9210	30.720	53.759	0.757	-0.590	0.196
ROL	054	10	9210	30.720	53.719	0.398	-0.324	0.162
ROL	054	11	9210	30.720	53.736	0.451	-0.607	0.168
ROL	054	12	9210	30.720	53.730	0.441	-0.449	0.140
ROL	054	13	9210	30.720	53.736	0.569	-0.317	0.127
ROL	054	14	9210	30.720	53.748	0.283	-0.727	0.169
ROL	054	15	9210	30.720	53.748	0.253	-0.516	0.111
ROL	054	16	9210	30.720	53.737	0.590	-0.450	0.147
ROL	054	17	9210	30.720	53.793	0.516	-0.561	0.161

RECORDED FROM: 9 pm 20 MAY -- 6 am 21 MAY 1975

TABLE I

GYRO	RUN	NUMBER	SEGMENT POINT COUNT	TIME (MINUTES)	TREND (MERU)	RESIDUE (APCSEC)	SIGMA	
						MAX	MIN	
PIT	057	1	9216	30.720	- 79.272	0.401	-0.269	0.092
PIT	057	2	9216	30.720	- 79.371	0.323	-0.31 ^a	0.096
PIT	057	3	9216	30.720	- 79.327	0.338	-0.408	0.108
PIT	057	4	9216	30.720	- 79.355	0.491	-0.175	0.100
PIT	057	5	9216	30.720	-779.410	0.665	-0.291	0.156
PIT	057	6	9216	30.720	- 79.488	0.627	-0.328	0.137
PIT	057	7	9216	30.720	-779.322	0.379	-1.490	0.434
PIT	057	8	9216	30.720	-779.255	0.412	-0.345	0.118
PIT	057	9	9216	30.720	- 79.305	0.944	-0.452	0.290
PIT	057	10	9216	30.720	-79.344	0.253	-0.516	0.12 ^a
PIT	057	11	9216	30.720	-779.211	0.292	-0.32 ^a	0.068
PIT	057	12	9216	30.720	-779.216	0.440	-0.302	0.114
PIT	057	0	326	1.087	-779.280	0.337	-0.135	0.083

RECORDED FROM: 10 am -- 4 pm 21 MAY 1975

TABLE 2

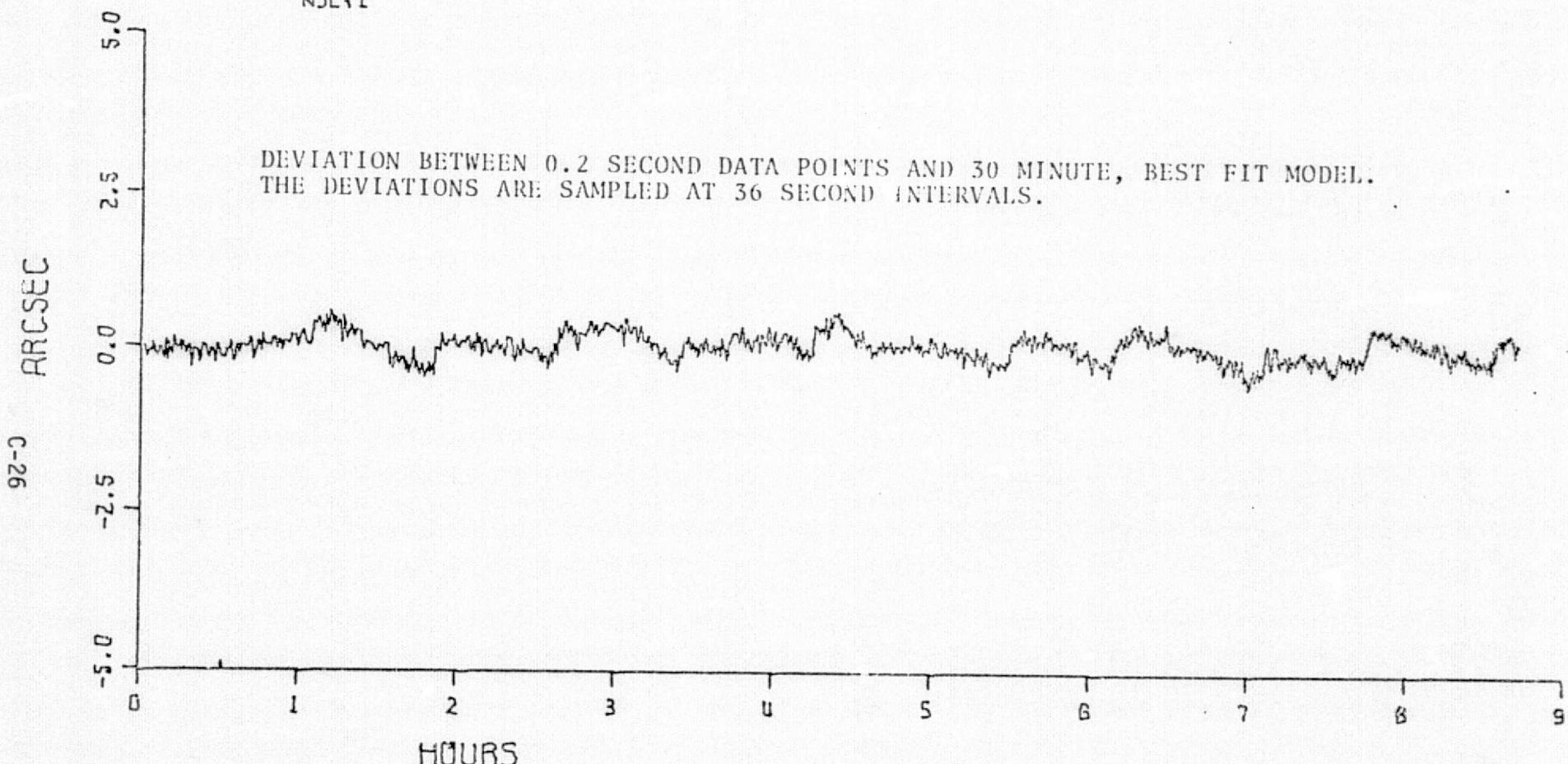
REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

GYPO	RUN	NUMBER	SEGMENT POINT COUNT	TIME (MINUTES)	TREND (MERU)	RESIDUE (ARCSEC)		
						MAX	MIN	SIGMA
YAW	058	1	9210	30.720	-20.176	2.652	-3.187	1.672
YAW	058	2	9210	30.720	-720.120	3.332	-1.331	0.965
YAW	058	3	9210	30.720	-719.999	7.321	-0.299	2.192
YAW	058	4	9210	30.720	-719.699	0.782	-5.135	1.620
YAW	058	5	9210	30.720	-720.364	3.325	-1.502	1.200
YAW	058	6	9210	30.720	-20.231	0.913	-5.477	1.035
YAW	058	7	9210	30.720	-719.844	4.619	-2.220	2.165
YAW	058	8	9210	30.720	-20.159	0.389	-4.517	1.177
YAW	058	9	9210	30.720	-720.746	6.035	-0.444	1.375
YAW	058	10	9210	30.720	-720.552	0.840	-7.444	2.451
YAW	058	11	9210	30.720	-720.248	1.635	-2.192	0.981
YAW	058	12	9210	30.720	-720.995	0.799	-2.738	1.361
YAW	058	13	9210	30.720	-720.213	1.517	-5.536	1.071
YAW	058	14	9210	30.720	-720.591	6.422	-0.169	1.615
YAW	058	15	9210	30.720	-721.028	2.454	-1.424	1.173
YAW	058	16	9210	30.720	-720.751	4.738	-3.672	2.015
YAW	058	17	9210	30.720	-720.862	2.521	-3.695	1.759

RECORDED FROM: 11 pm 22 MAY -- 8 am 23 MAY 1975

TABLE 3

DRD DRU TEST GSFC
ATTITUDE ERROR ROLL AXIS
20 TO 21 MAY 1975
NSLTL



MMEAN	.02817928	ARCSEC
SIGMA	.1984	ARCSEC
TREND	-.005067	ARCSEC
SIGMA/TREND	.1980	ARCSEC
SAMPLE PERIOD	36.00	/HOURS
REJECTED POINTS 0	OUT OF 671	SECONDS
		SAMPLES

Fig 12

SOS TEST LRB IS K C.R.B.

ORD IRU TEST GSFC
ATTITUDE ERROR PITCH AXIS
2L TO 22 MAY 1975
NSLTL

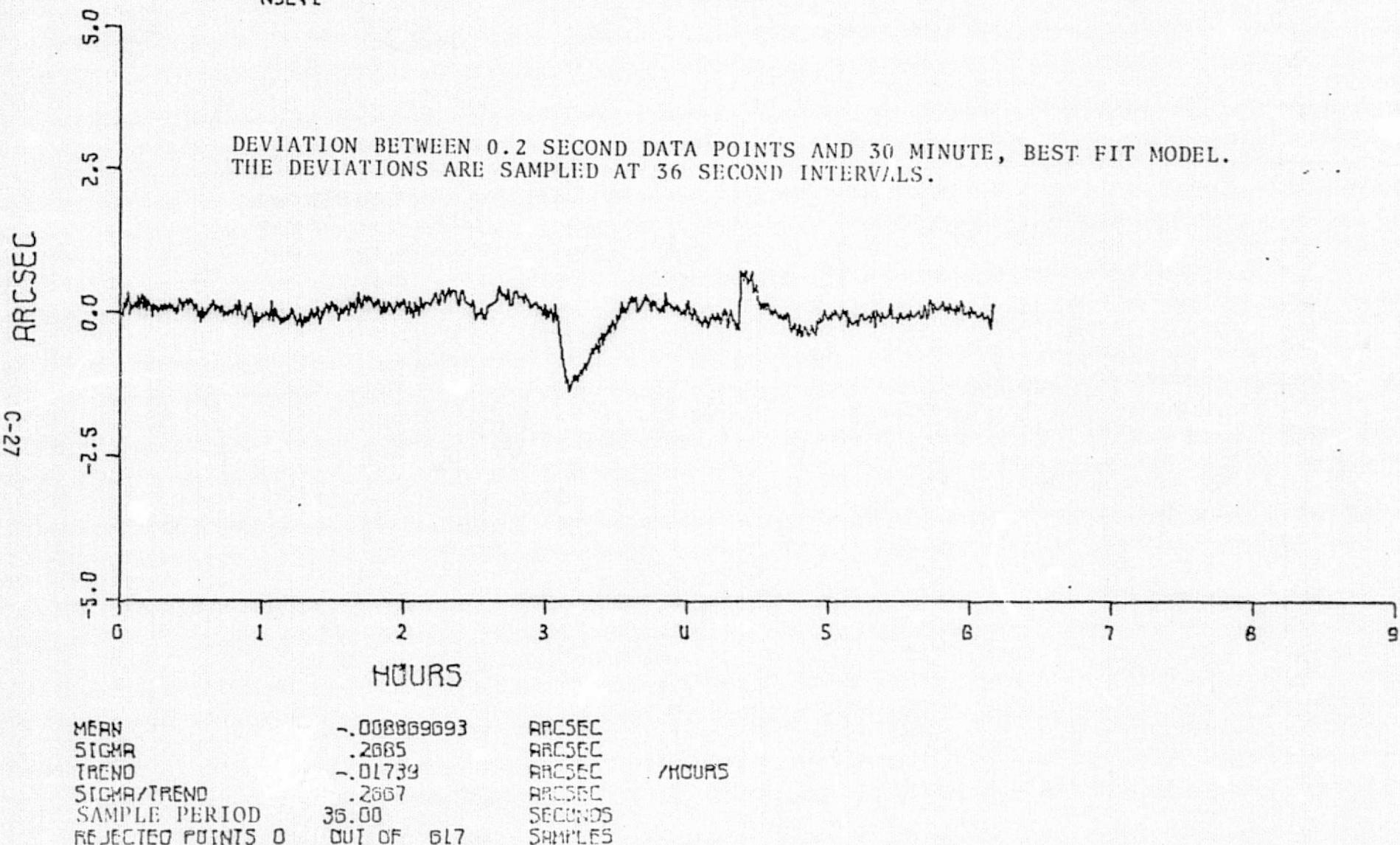
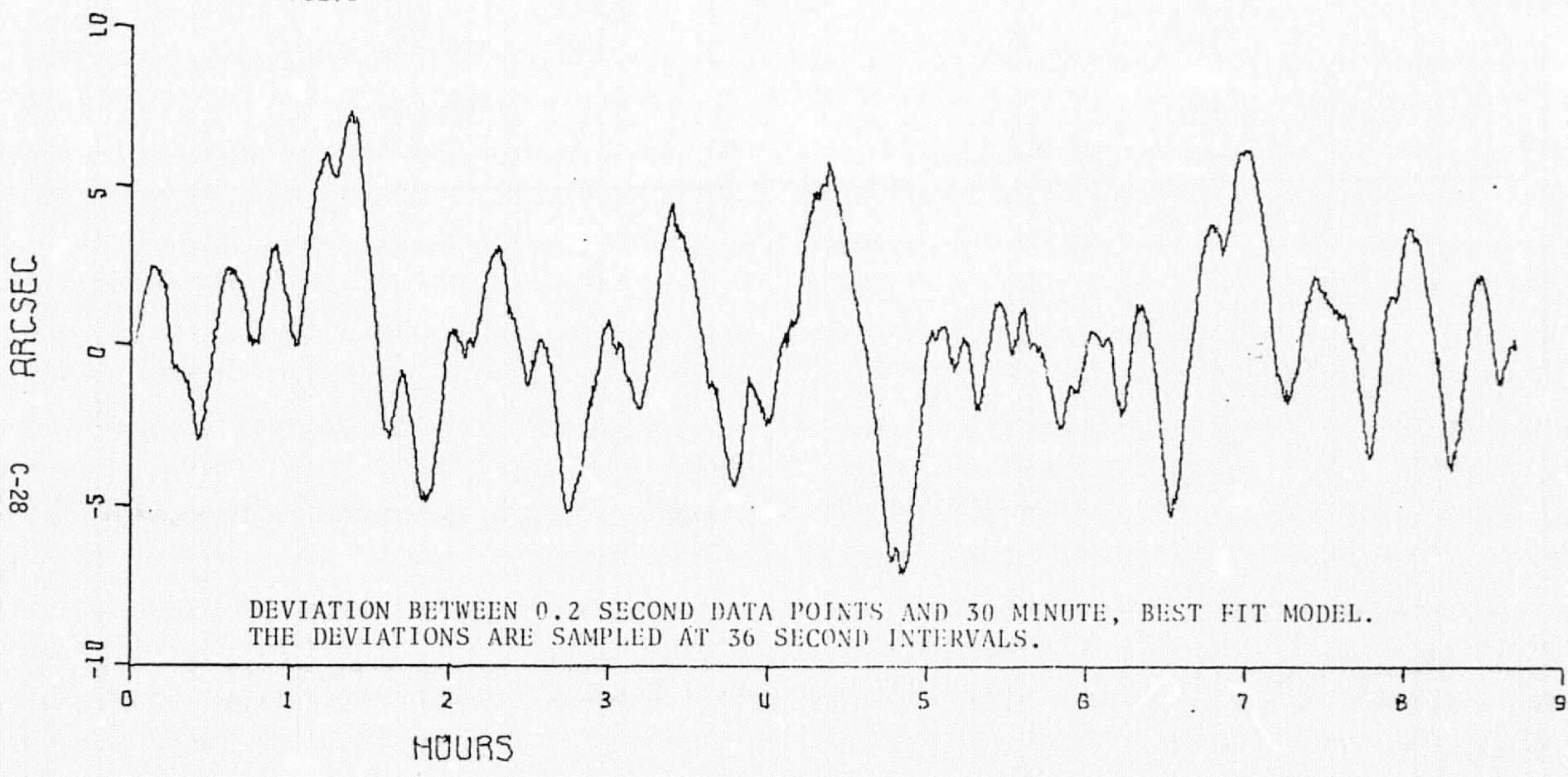


Fig 13

SUS TEST LAB 15 K G.R.B.

ODD INJ TEST GSFC
ATTITUDE ERROR YAW AXIS
22 TO 23 MAY 1975
NSL41



MEAN	.2039577	ARCSEC
SIGMA	2.6978	ARCSEC
TREND	-.04560	ARCSEC
SIGMA/TREND	2.6954	ARCSEC
SAMPLE PERIOD	36.00	SECONDS
REJECTED POINTS 0	OUT OF 671	SAMPLES

Fig. 14

SOS TEST LAB 15 K G.R.B.



TO: R. Harris

FROM: R. Carson *R.C.C.*

DATE: 6 November 1975

SUBJECT: OAO-IRU Engineering Model Data at TRW September 1975

Approximately sixty hours of gyro data was obtained from the OAO-IRU Engineering Model at TRW, Redondo Beach, California during September 1975. This data is displayed in both time and power spectral density plots. The time histories provide an indication of the overall instrument performance and the PSD data can indicate the performance that can be expected in a particular frequency range. A brief description of the data accumulated is enclosed.

Time Plots

Three data sets were recorded simultaneously for each of the three instruments and are shown in Figures 1 through 9. The details of each set are described below:

Data Set	Run	Sample Period	Length of Test	Date
1	72	.32 seconds	9 hours	8-9 Sept
2	73	2.56 seconds	32 hours	9-10 Sept
3	74	2.56 seconds	16 hours	10-11 Sept

It can be seen from the time plots that the output of each gyro is consistent from test to test. It should also be noted that the roll and pitch instruments exhibit approximately 0.1 meru jumps within three stable states. It is further observed that these discontinuities occur simultaneously and are quite deterministic

with an overall period of approximately 17 hours. The yaw gyro on the other hand is quite erratic with frequent spikes of approximately 3 meru and occasional spikes greater than 10 meru. Needless to say, the erratic behavior of the yaw gyro and the discontinuities in the roll and pitch instruments are not considered normal. However this performance is an improvement by approximately a factor of 10 over that which was observed at GSFC in June. The roll and pitch gyros would be considered quite acceptable without the jumps. Again it is felt that the anomalous behavior of the instruments is the result of an unknown malfunction within the Engineering Model.

PSD Plots

The results of the PSD analysis are shown in Figures 10 through 18. The data are plotted as single sided PSDs (i.e., all the energy exists in the frequency range of 0 to ∞) in rate and have units of "meru²/Hz". Selected portions of each of the three data sets were chosen to characterize the instrument output under various conditions and different frequency ranges. Figures 10 through 12 are the PSD of approximately 1.5 hours from data set 1 with no discontinuities. Figures 13 through 15 are the resultant PSDs of approximately 12 hours from data set 3 with several jumps. Figures 16 through 18 show the PSD plots of the first 24 hours of data set 2.

Each of the PSDs has two distinct characteristics: a positive slope at the high frequencies and a negative slope at the low frequencies. The positive slopes are proportional to f^2 and are attributed to quantization noise due to the sampling process. It will be noted that the levels of the PSDs calculated from 2.56 second data samples (Runs 73 and 74) are eight times higher than those calculated using 0.32 second samples (Run 72). This is consistent with modelling quantization noise as a white process in angle and band limited at the Nyquist frequency of the sample

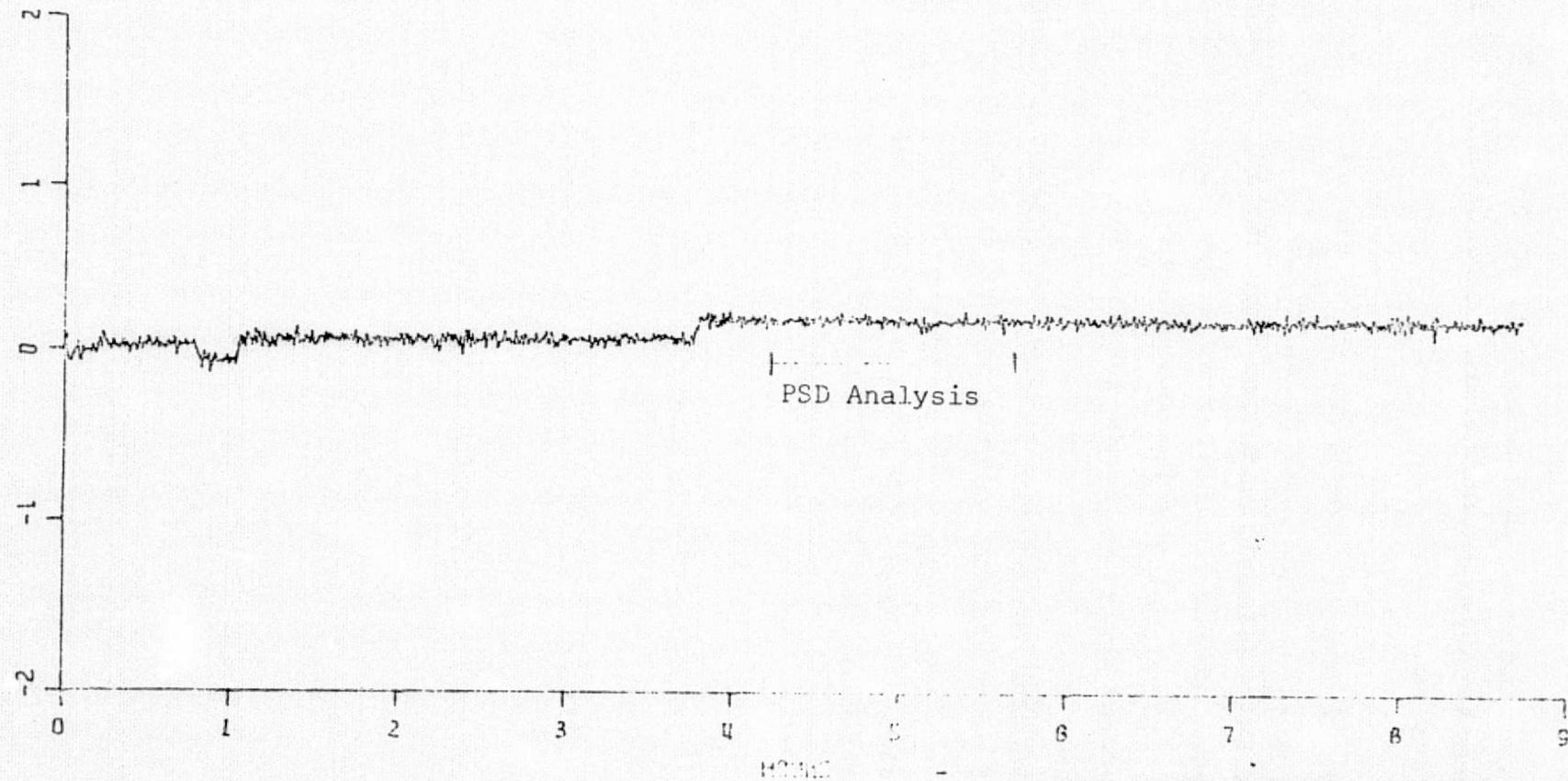
rate. The remainder of this memo will concentrate on the low frequency characteristics which are attributed to the gyros and to the system.

Figures 10 and 11 illustrate the behavior of the roll and pitch instruments without the presence of jumps and compares favorably with previously obtained data with other 2FBG-6F gyros. Figure 12 further illustrates the erratic behavior of the yaw axis gyro. At the low frequencies, the PSD of the yaw gyro is approximately 100 times greater than those for the other two axes even though the data used to generate the yaw PSD plot did not include any spikes. Figures 13 through 18 are the PSDs of each instrument when spikes or discontinuities are present. The deterministic jumps in each of the axes not only increases the magnitude of the PSD but also change its characteristics at the lower frequencies.

RCC/alk

SKYLAB DATA TAW CHANNEL M1 ROLL AXIS
SEPTEMBER 8 TO SEPTEMBER 9, 1975

C-32



REFERENCE VALUE	MEAN	SD	MEAN	SD
MEAN	0.741, 0.913	0.751, 0.733	MEAN	0.741
SD	0.004	0.004	SD	0.004
TD(1)	0.00112	0.00112	TD(1)	0.00112
TD(2)	0.00112	0.00112	TD(2)	0.00112
HYDRODYNAMIC	0.00112	0.00112	HYDRODYNAMIC	0.00112
HYDRODYNAMIC PERIOD	38.39	38.39	HYDRODYNAMIC PERIOD	38.39
DATA POINTS	0	0	DATA POINTS	0
DATA POINTS PER UNIT	1	1	DATA POINTS PER UNIT	1

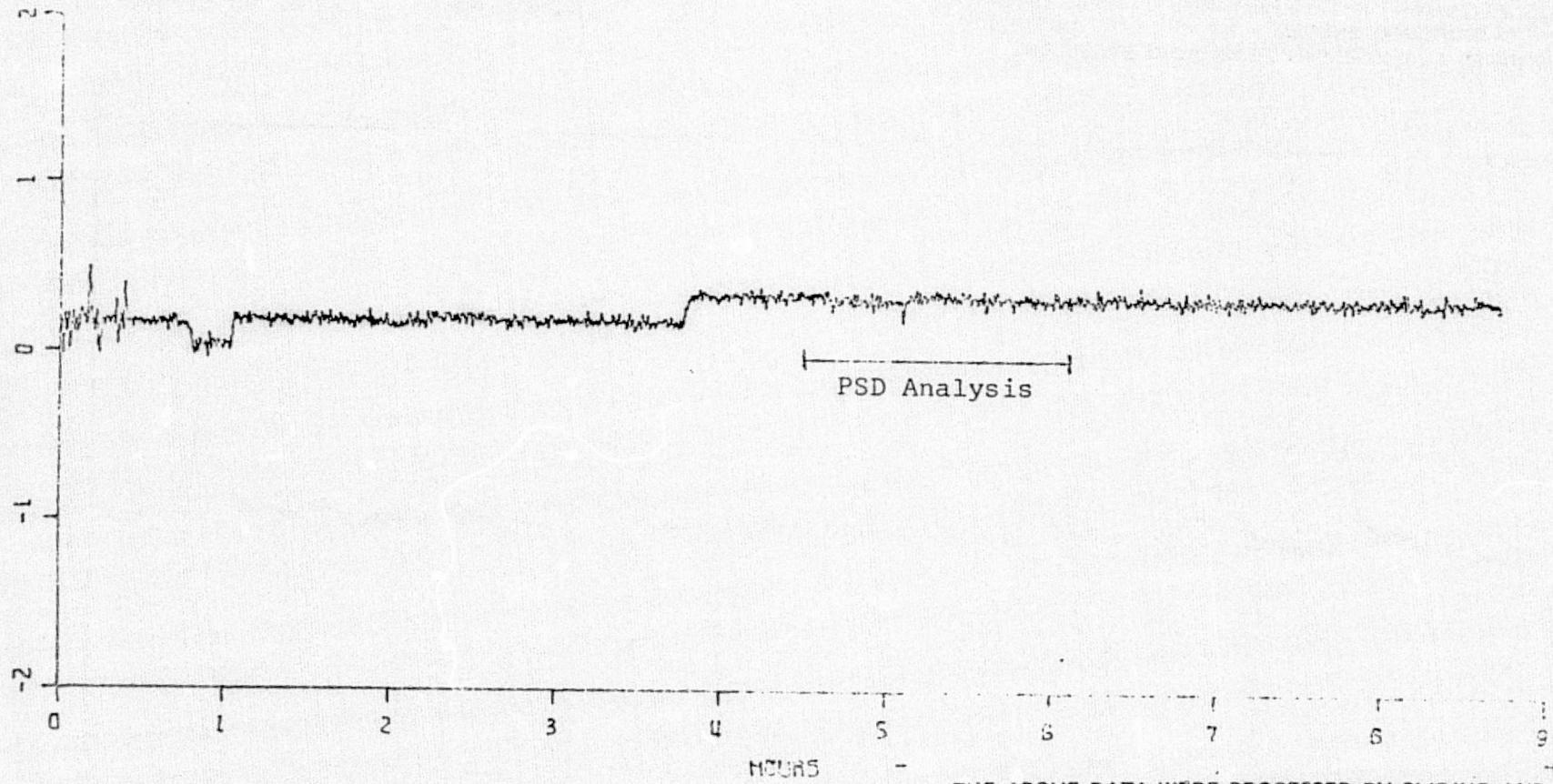
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 1/20, 32 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
0.014 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 1

DA-IRU DATA TAU CHANNEL M2 PITCH AXIS
SEPTEMBER 8 TO SEPTEMBER 9, 1975



THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 1120 .32 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

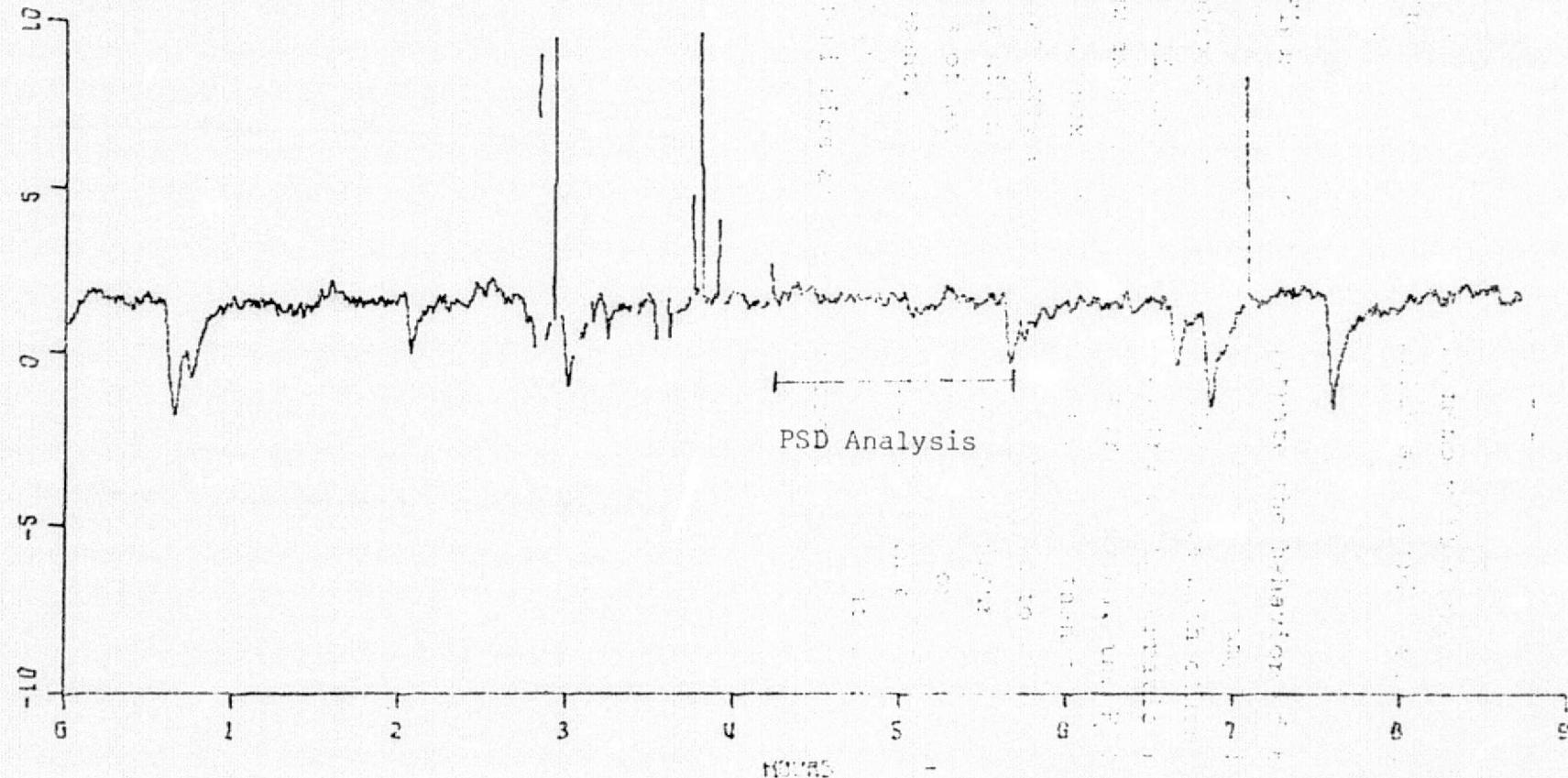
(-2) Effective Bandwidth
0.014 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 2

C-34

DRC-TRW DATA TRW CHANNEL M3 YAW RX15
SEPTEMBER 8 TO SEPTEMBER 9, 1975



REFERENCE VALUE	-643.04909	MEAN
MEAN	-641.67007	MEAN
STOKE	.6463	MEAN
TREND	.01214	MEAN
STOKE/TREND	.0158	MEAN
AVERAGE PERIOD	35.64	MEAN
MEANING POINTS 23	OUT OF 647	SAMPLES
MIN-MAX 0.13M		

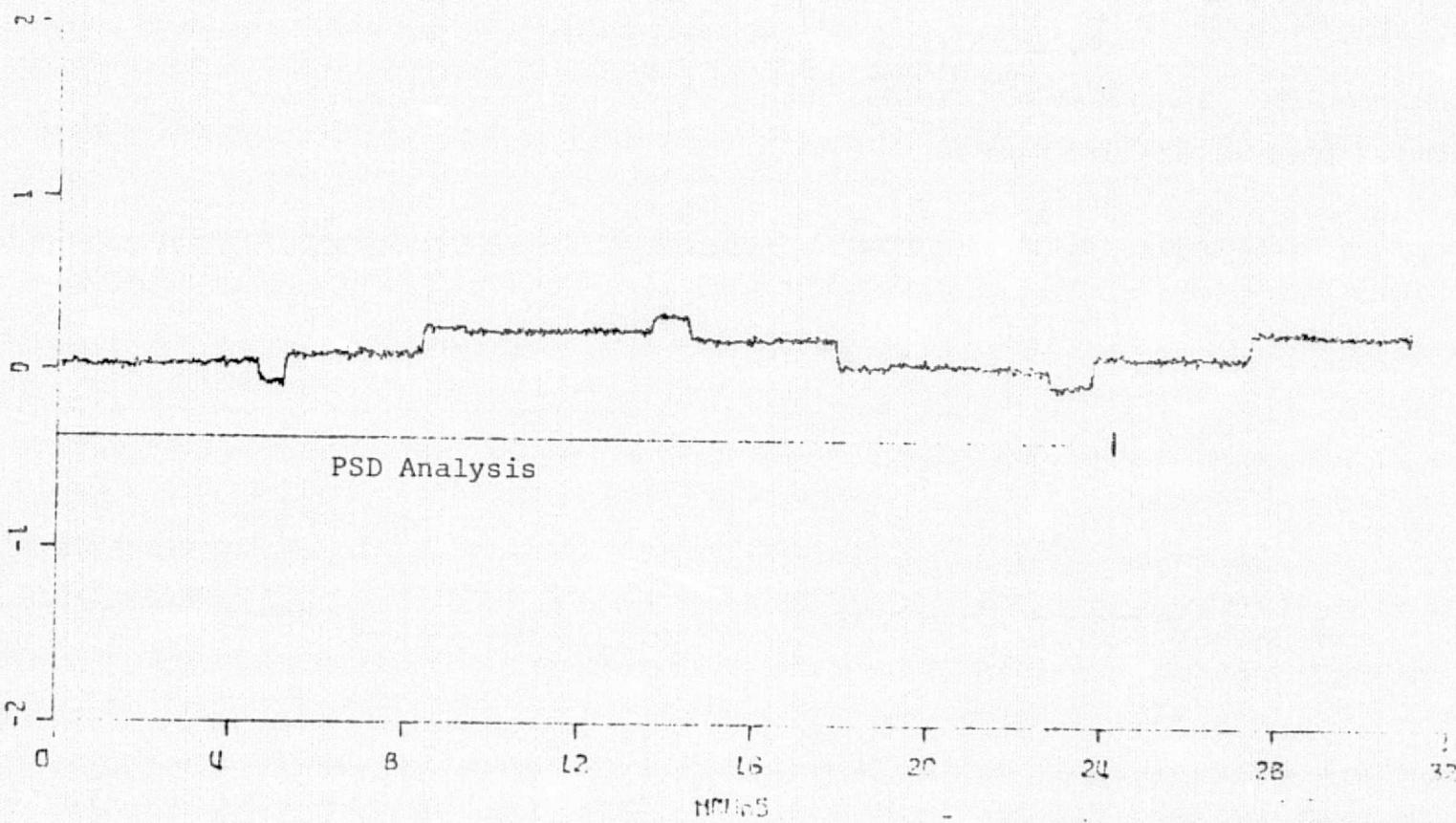
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING //2 , .32 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
0.014 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 3

DAD-TRU DATA TRW CHANNEL M2 FILTER AXIS
SEPTEMBER 9 TO SEPTEMBER 10, 1975



THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 500 .154 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

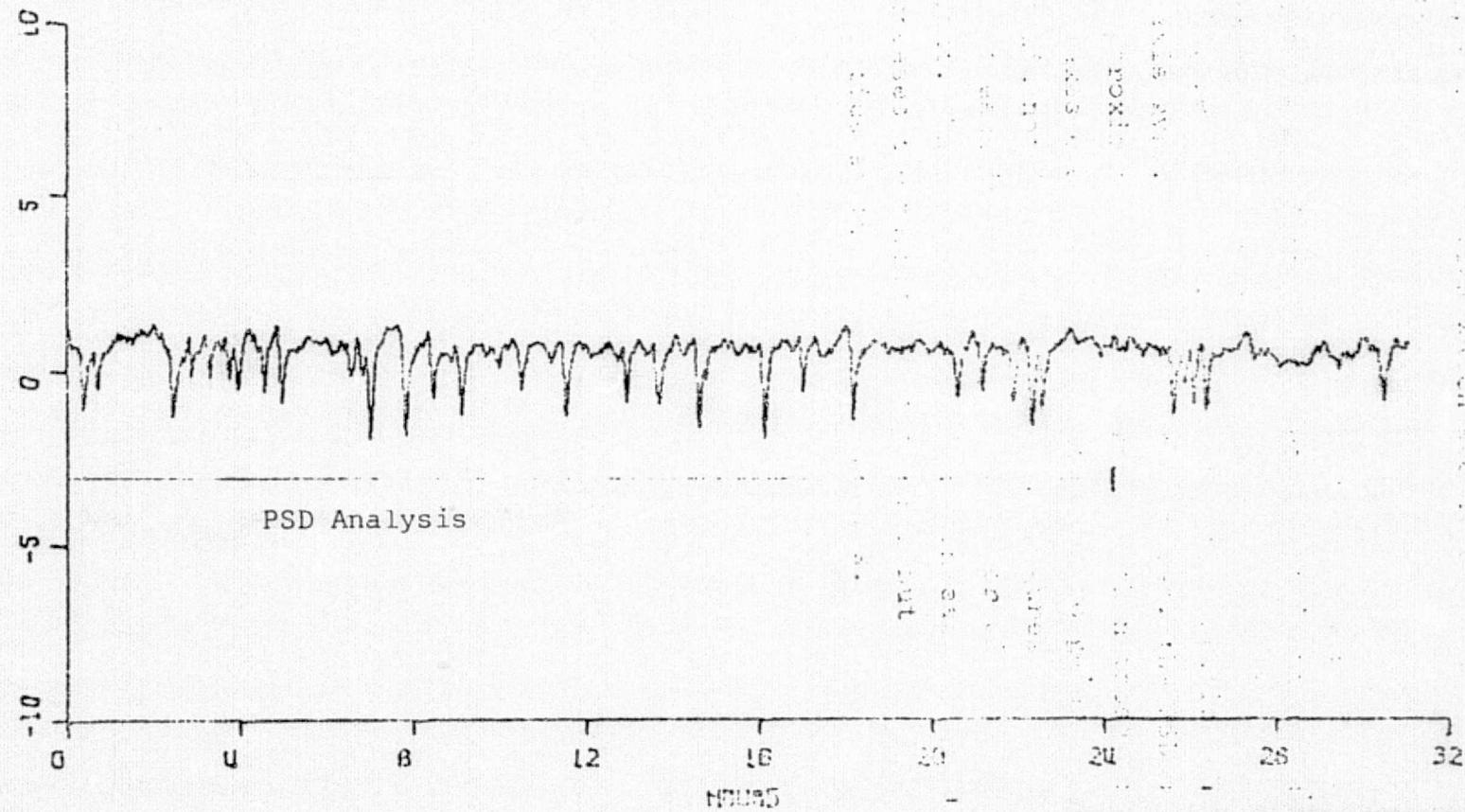
(-2) Effective Bandwidth
0.0035 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 5

C-37

DSD-1MU DSTR TRW CHANNEL M3 YAW AXIS
SEPTEMBER 9 TO SEPTEMBER 10, 1975



REFERENCE VALUE	-642.33430	PSD
MEAN	-641.87292	PSD
SD _{MEAN}	0.017	PSD
10 ² dB	-111.12	PSD
SD _{10² dB}	0.017	PSD
REF. POINTS 0	0.0000	PSD
DATA 0.0000	PSD	PSD

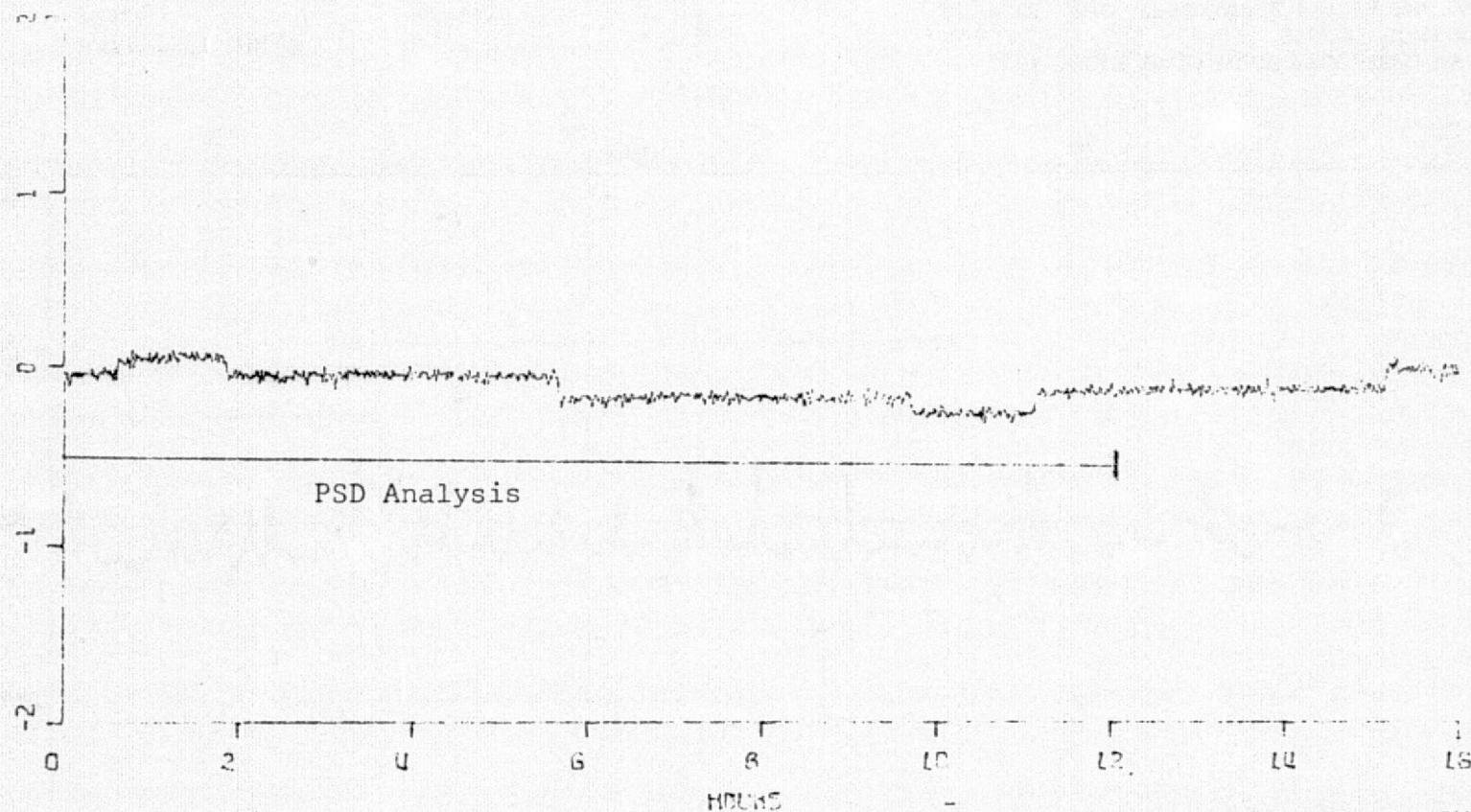
THE ABOVE DATA WERE PROCESSED BY SLIDING AND
AVERAGING 260, 2.56 SECOND CONTINUOUS DATA
SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS
DERIVED ARE:

(-2) Effective Bandwidth
0.0035 rad/s

SKIFER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 6

CAM-1H DATA TRW CHANNEL M1 BELL AXIS
SEPTEMBER 10 TO SEPTEMBER 11, 1975



THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 180 . 2.56 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

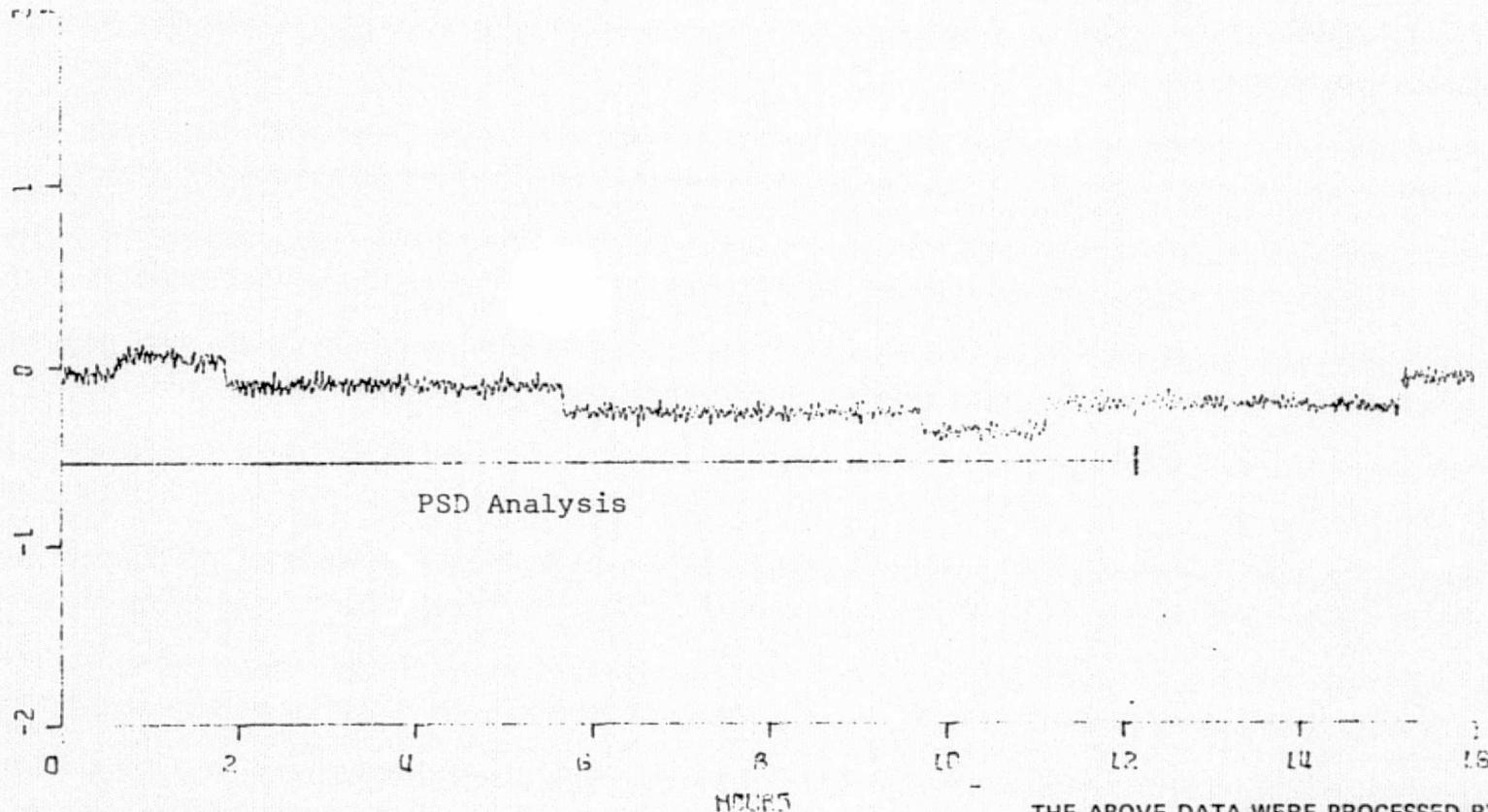
(-2) Effective Bandwidth
rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 7

C-39

DIA-CAU DATA TRW CHANNEL M2 PITCH AXIS
SEPTEMBER 10 TO SEPTEMBER 11, 1975



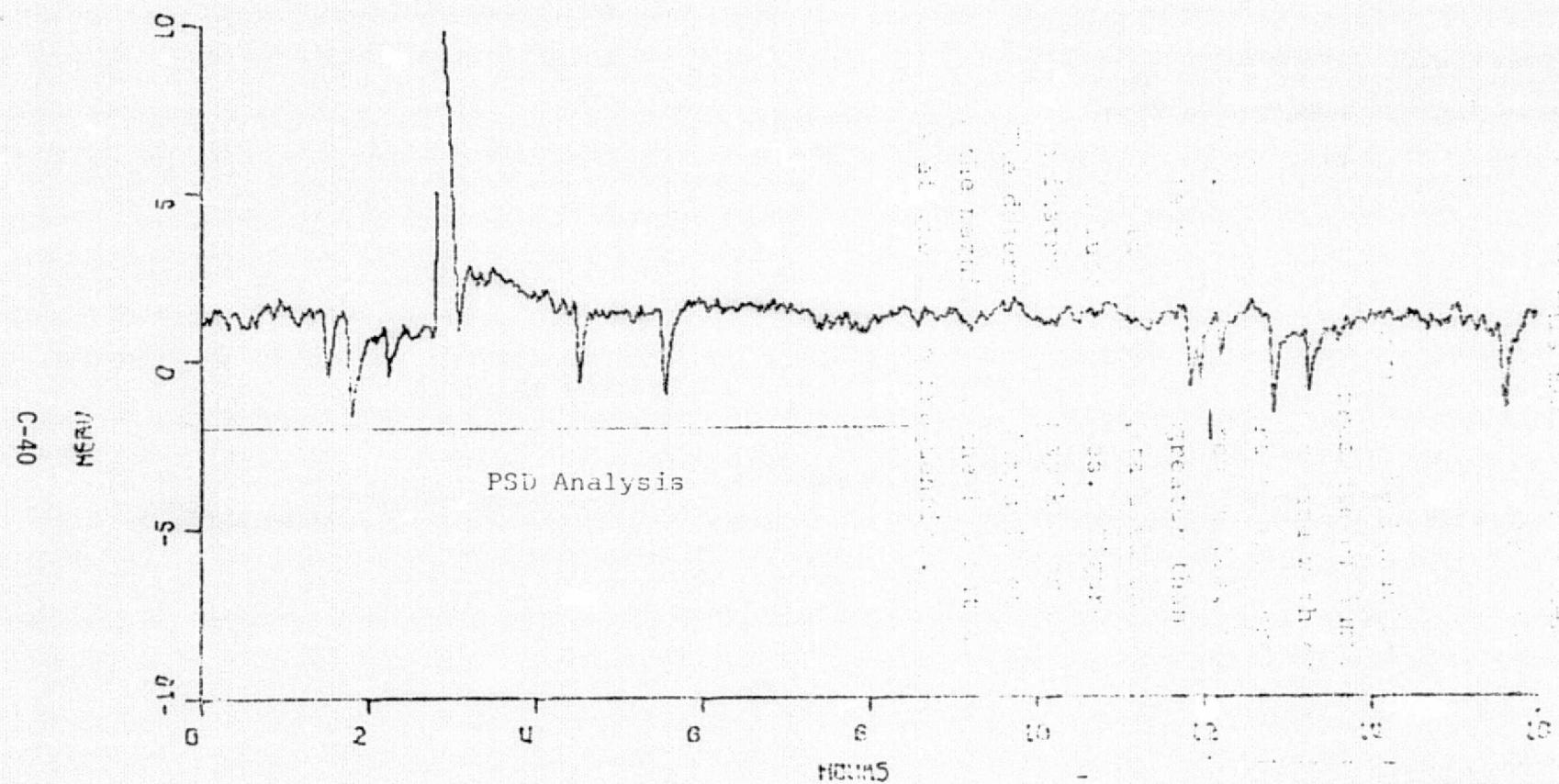
THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 2.56 - 2.56 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
0.007 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

FIGURE 8

DATA FROM DMR TEN CHANNEL NO. TWO RXIS
SIXTY-FIVE TO SIXTY-THREE 11, 1975



REFERENCE VALUE	-842.92593	MEAN
MAX	-841.78121	MEAN
MIN	.8104	MEAN
STDDEV	-08.317	MEAN
STRAIGHTEND	.78517	MEAN
MEASURING PERIOD	711.7	SD MEAN
MEASURED POINTS 4	OUT OF 510	SD MEAN
DATE-1/1/074M ?		SD MEAN

THE ABOVE DATA WERE PROCESSED BY SLIDING AND AVERAGING 180, 255 SECOND CONTINUOUS DATA SAMPLES. THE APPROXIMATE FILTER CHARACTERISTICS DERIVED ARE:

(-2) Effective Bandwidth
0.007 rad/s

SKIPPER K TEST LABORATORY/BEDFORD FLIGHT FACILITY

ROLL (0A0-IRU) 72

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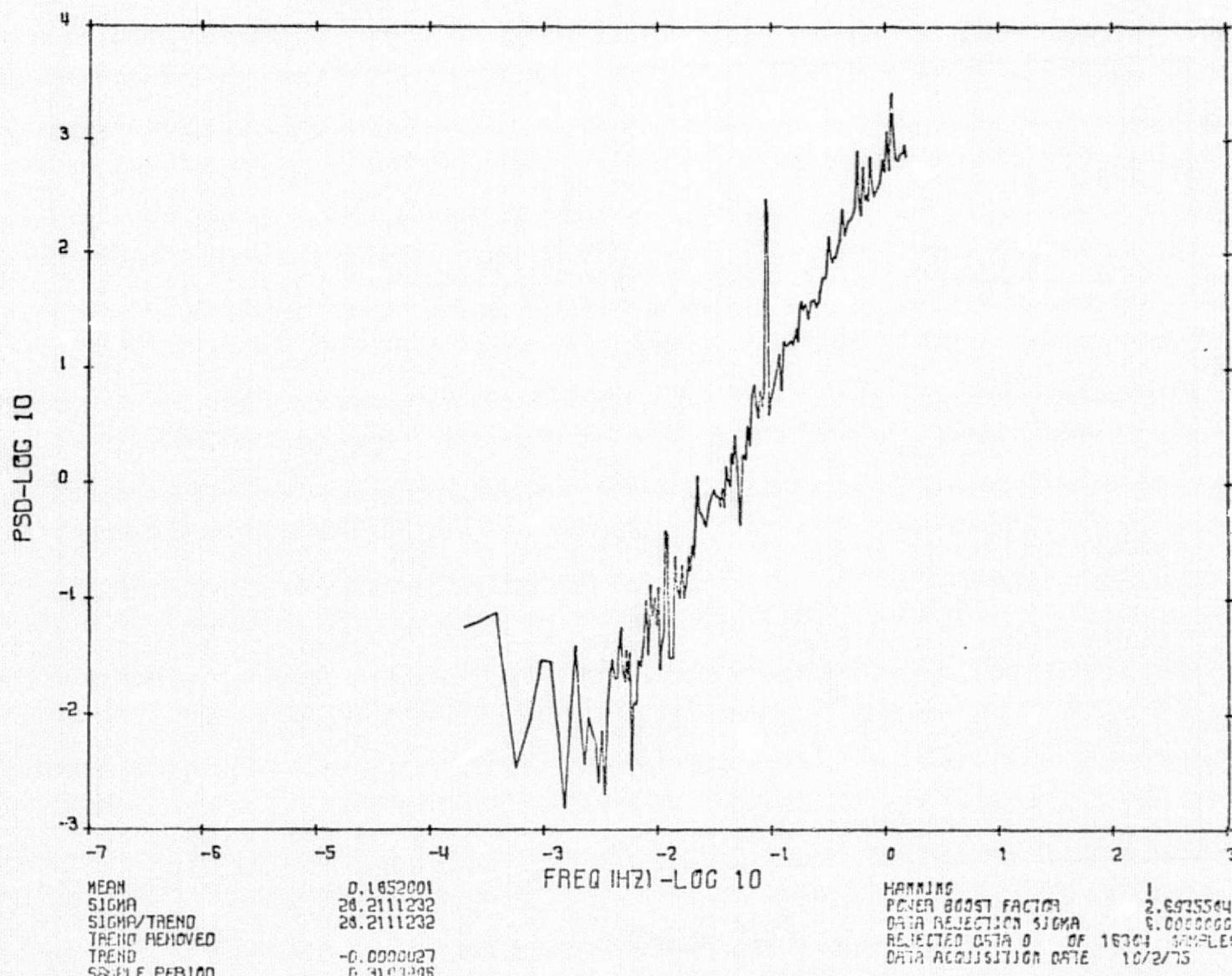


FIGURE 10

PITCH (0A0-IRU) 72

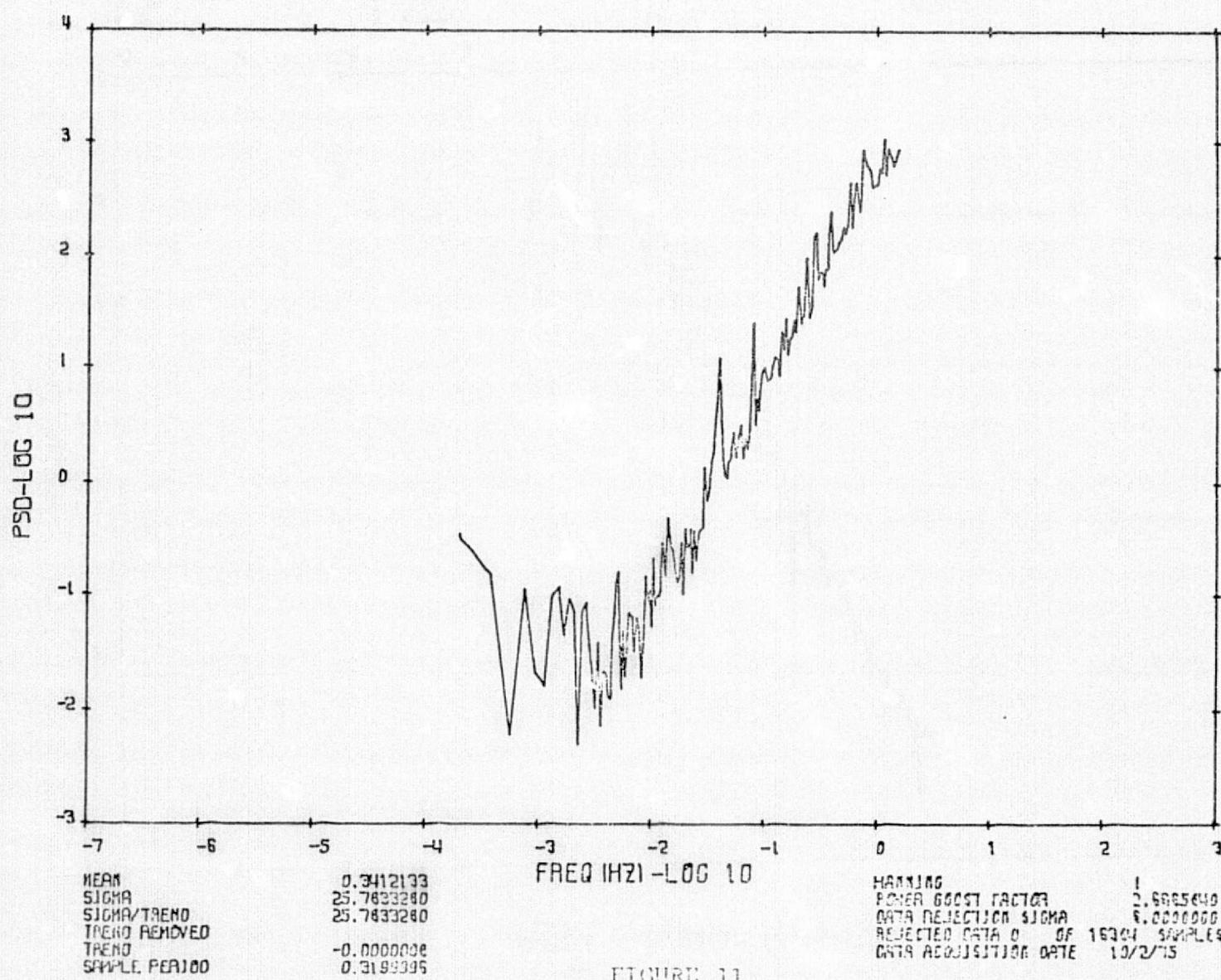
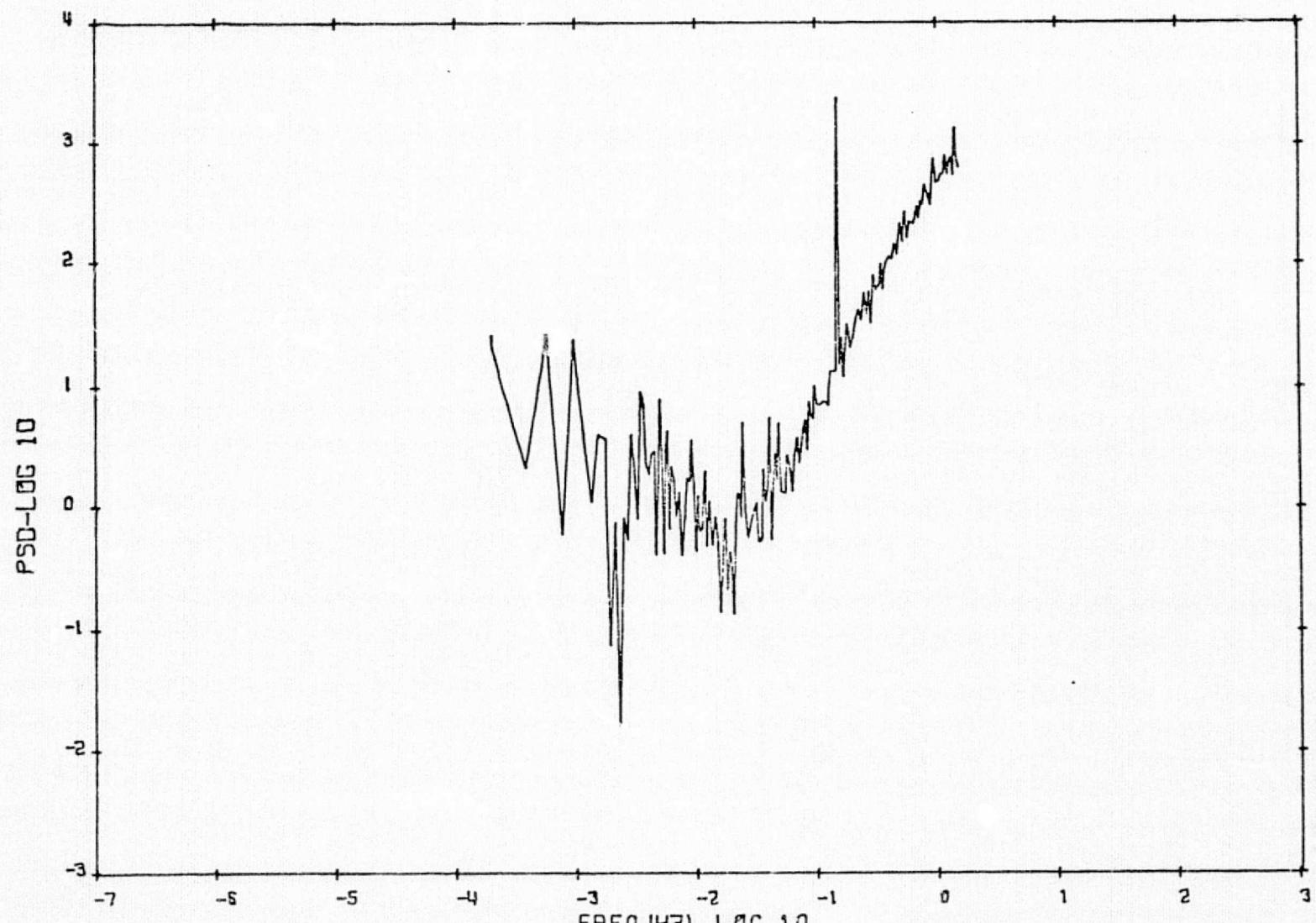


FIGURE 11

YAW (0A0-IRU) 72



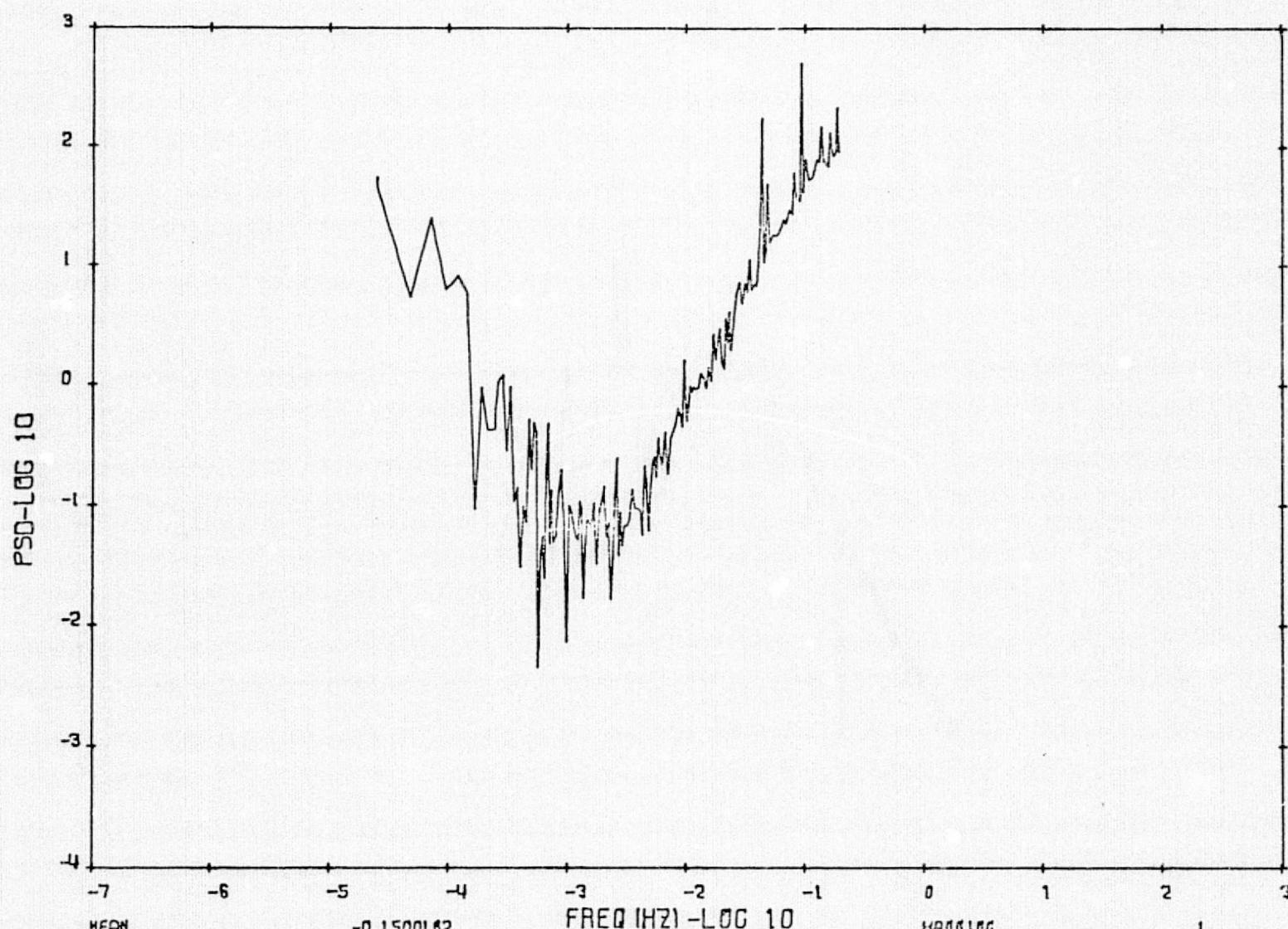
MEAN	1.605960
SIGMA	24.637370
SIGMA/TREND	24.637370
TREND REMOVED	
TREND	-0.0000129
SAMPLE PERIOD	0.318136

FIGURE 12

HARMING	1
POWER BOOST FACTOR	2.6069606
DATA REJECTION SIGMA	6.0000000
REJECTED DATA 3 OF 1634 SAMPLES	
DATA ACQUISITION DATE	10/2/75

ROLL (0A0-IRU) 74

C-44



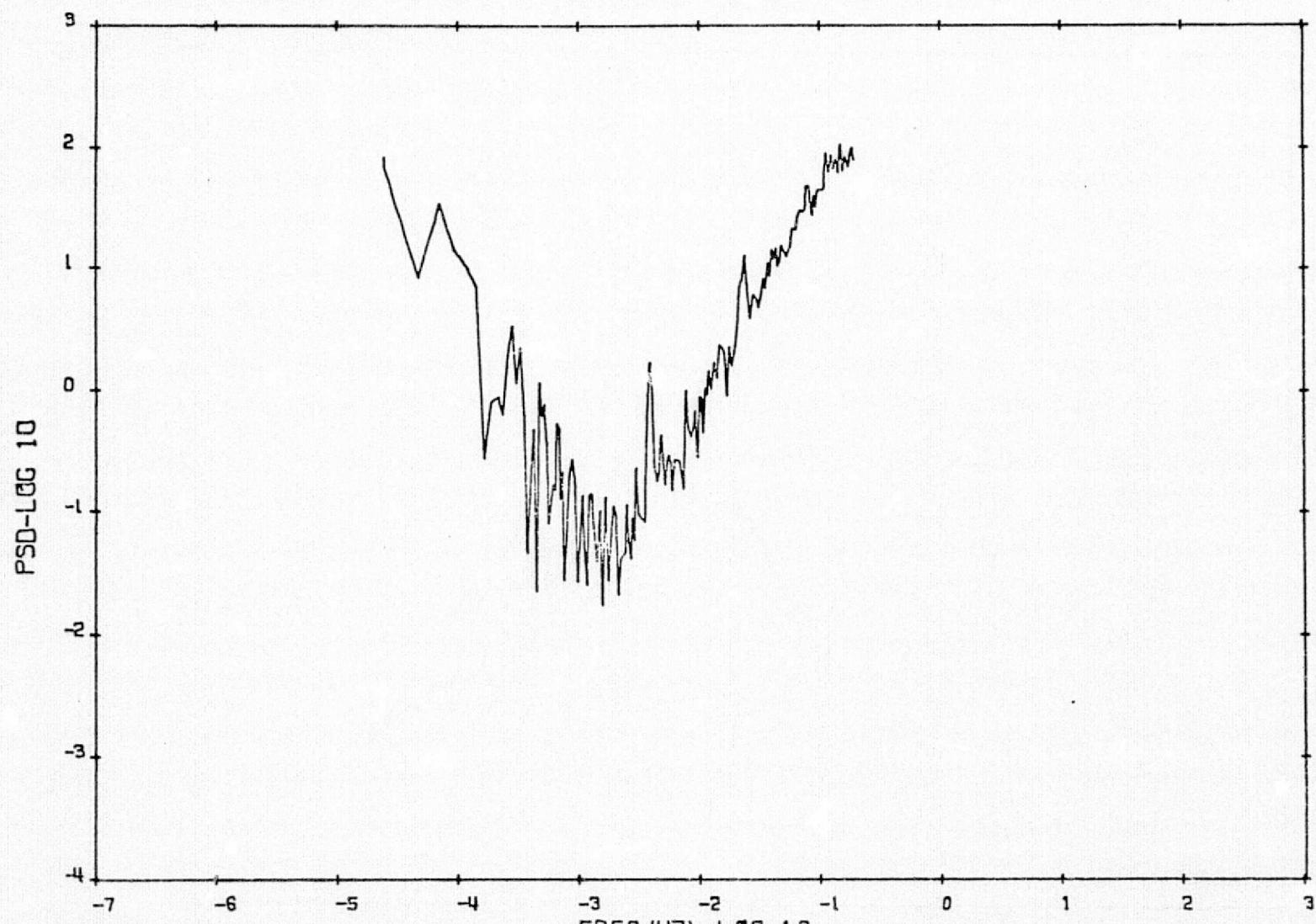
MEAN	-0.1500162
SIGMA	3.5126600
SIGMA/TREND	3.5125568
TREND REMOVED	
TREND	-0.0000024
SAMPLE PERIOD	2.5E-00668

FIGURE 13

HANNING	1
POWER BOOST FACTOR	2.7250495
DATA REJECTION SIGMA	6.0000000
REJECTED DATA C OF 16384 SAMPLES	
DATA ACQUISITION DATE	10/2/75

PITCH (0AO-IRU) 74

C-45

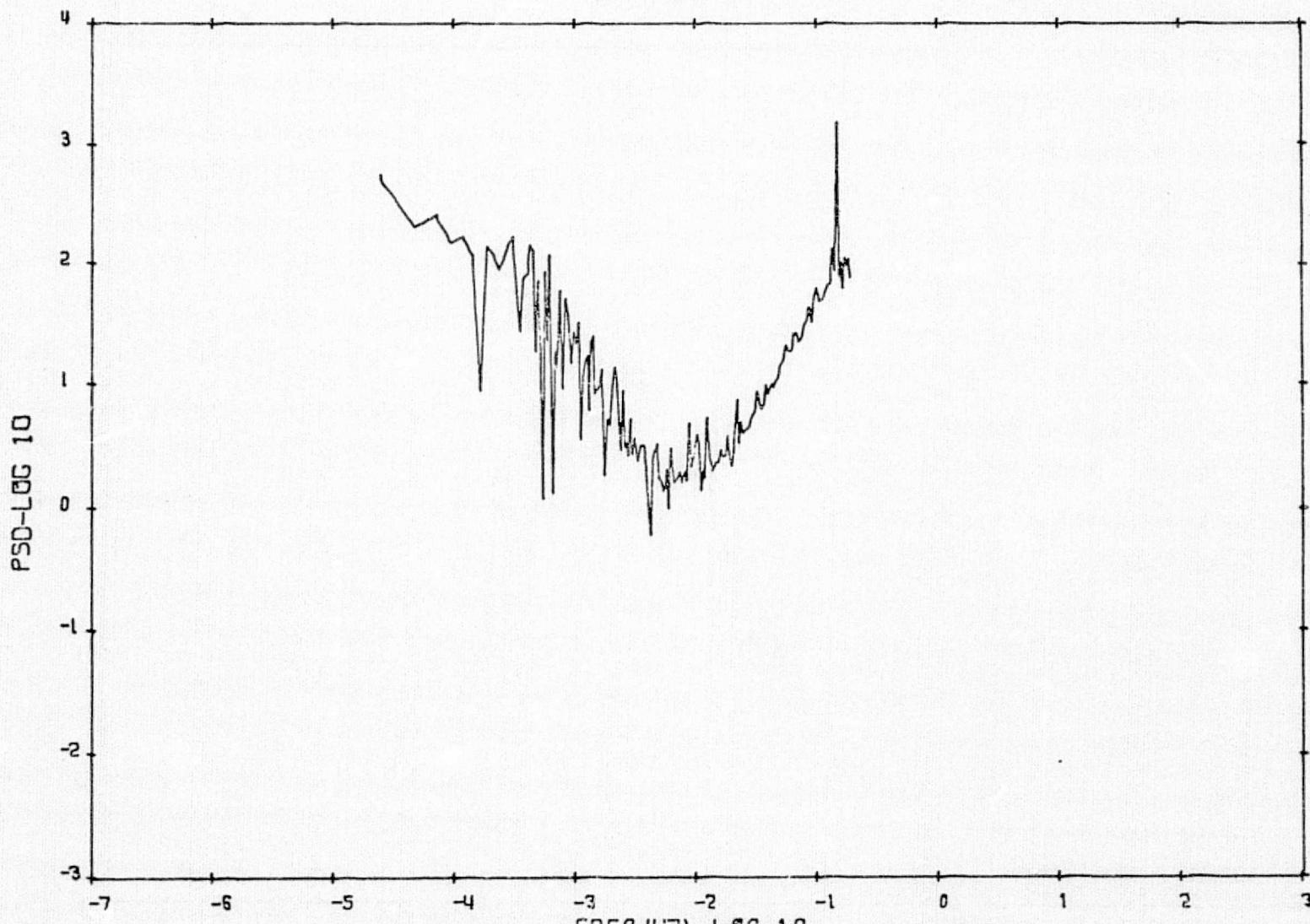


MEAN	-0.2206499
SIGMA	3.0266000
SIGMA/TREND	3.0263504
TREND REMOVED	
TREND	-0.0000032
SAMPLE PERIOD	2.5599968

FIGURE 14

HANNING	
POWER BOOST FACTOR	2.7034000
DATA REJECTION SIGMA	6.0000000
REJECTED DATA 0 OF 16364 SAMPLES	
DATA ACQUISITION DATE	10/2/75

YAW 10A0-IRU174



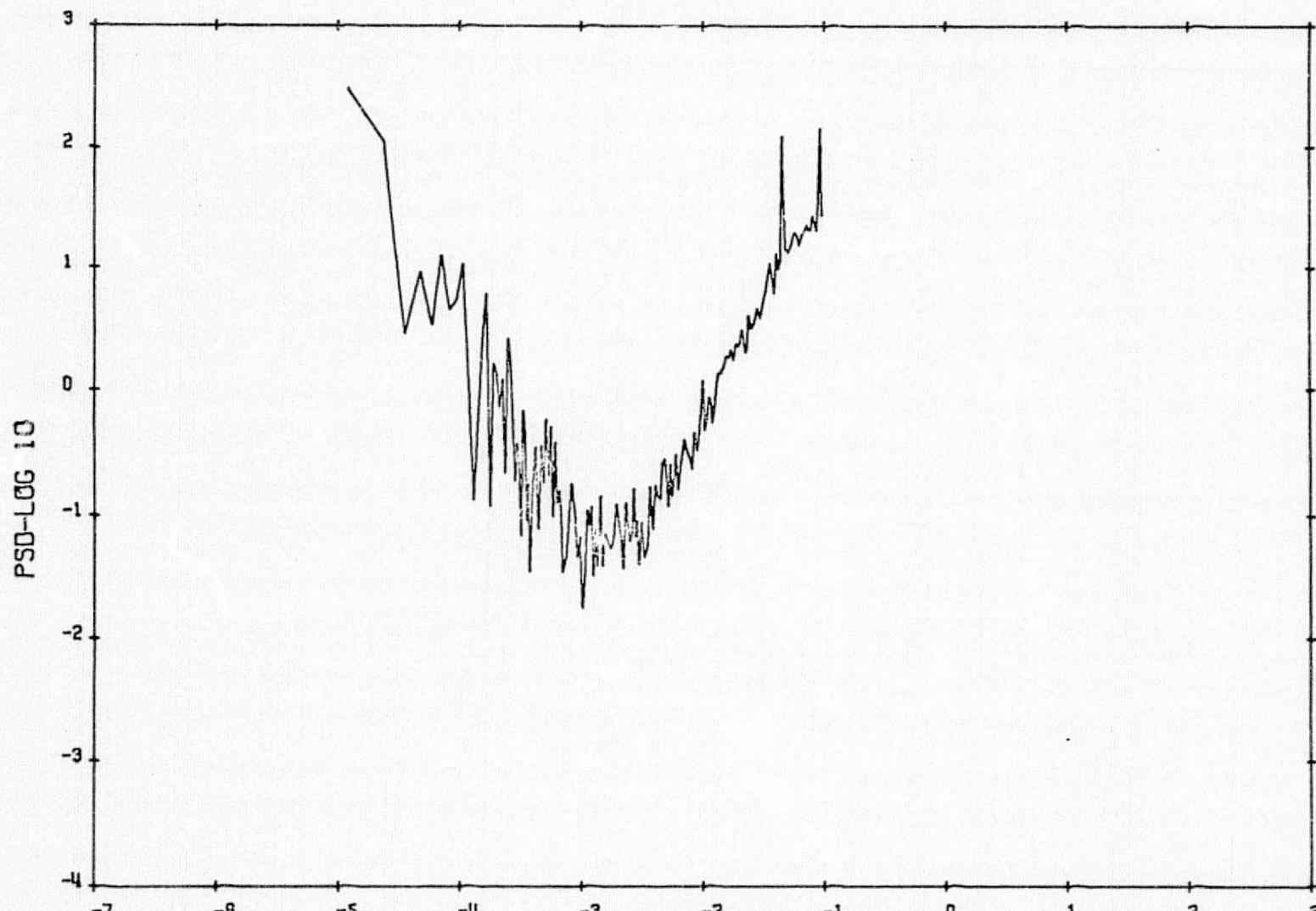
HANNING
POWER SPECTRUM FACTOR 1
DATA REJECTION SIGMA 5.0000000
REJECTED DATA 0 OF 16344 SAMPLES
DATA ACQUISITION DATE 10/2/15

FIGURE 15

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

C-46

ROLL (0AO-IRU) 73



C-47

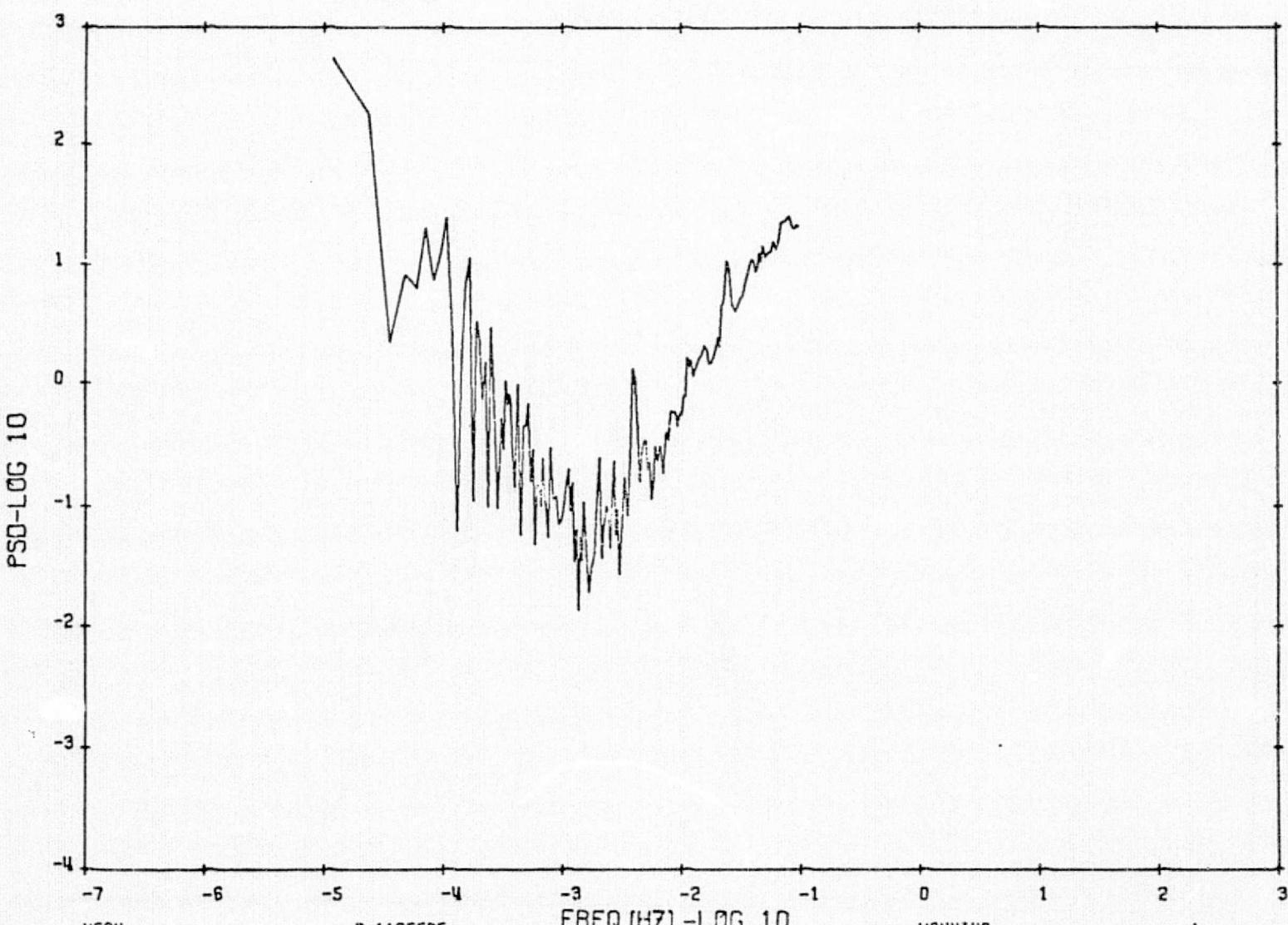
MEAN
SIGMA
SIGMA/TREND
TREND REMOVED
TREND
SAMPLE PERIOD

0.0937456
1.3671160
1.3000800
0.0000010
5.1195536

FIGURE 16

HANNING
POWER BOOST FACTOR 1
DATA REJECTION SIGMA 2.6893136
REJECTED DATA 0 OF 16364 SAMPLES
DATA ACQUISITION DATE 6.0000000
9/10/75

PITCH (0A0-IRU) 73



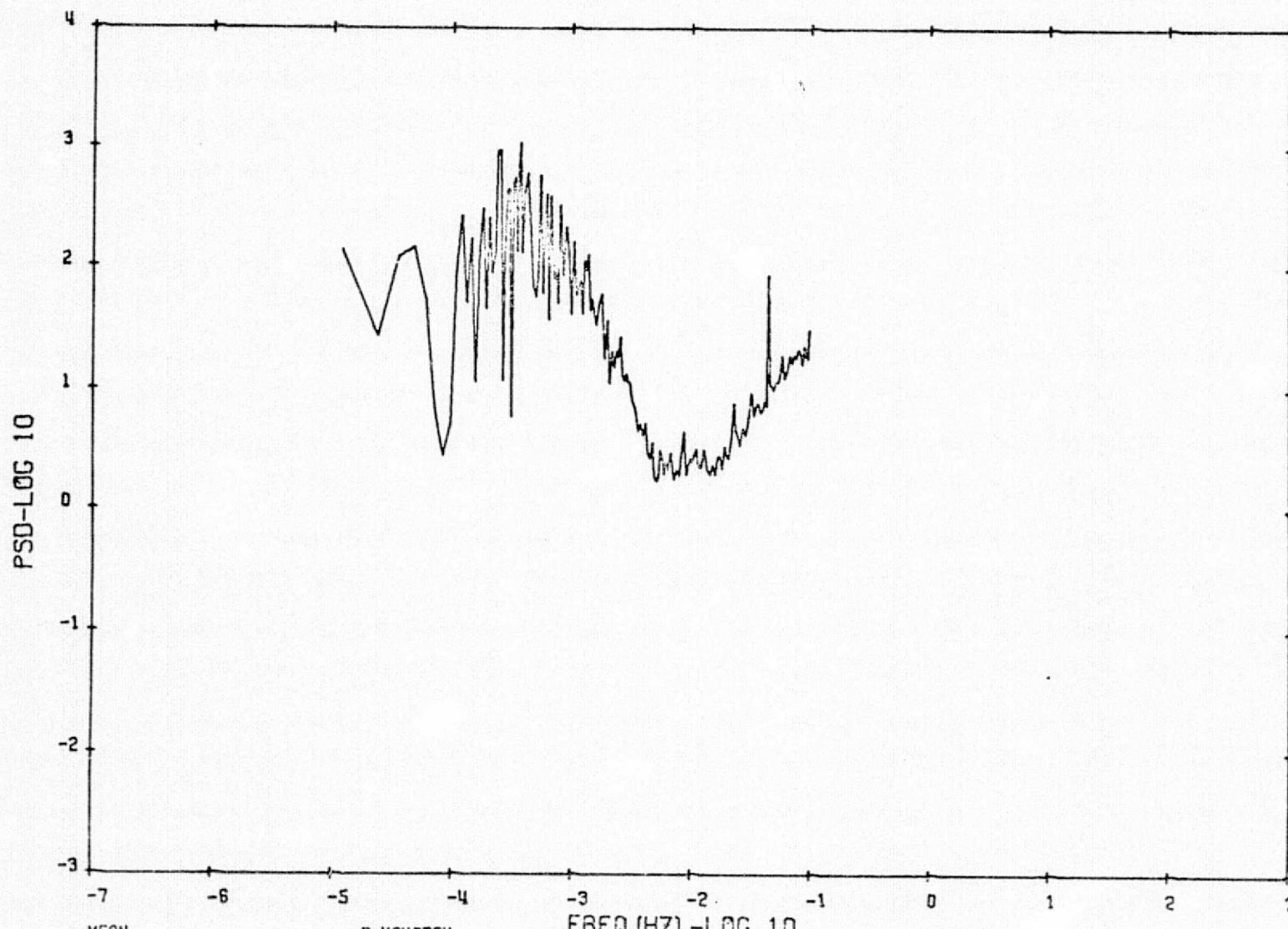
MEAN	0.1135585
SIGMA	1.1011910
SIGMA/TREND	1.1011570
TREND REMOVED	
TREND	0.0000004
SAMPLE PERIOD	5.1155536

FIGURE 17

HANNING	1
POWER BOOST FACTOR	2.0016448
CATA REJECTION SIGMA	6.0000000
REJECTED DATA 0 OF 16364 SAMPLES	
DATA ACQUISITION DATE	9/10/75

C-49

YAW (0A0-IRU) 73



MEAN
SIGMA
SIGMA/TREND
TREND REMOVED
TREND
SAMPLE PERIOD

0.4648734
1.2555710
1.25561630
-0.0000013
5.1150956

FREQ (HZ) -LOG 10

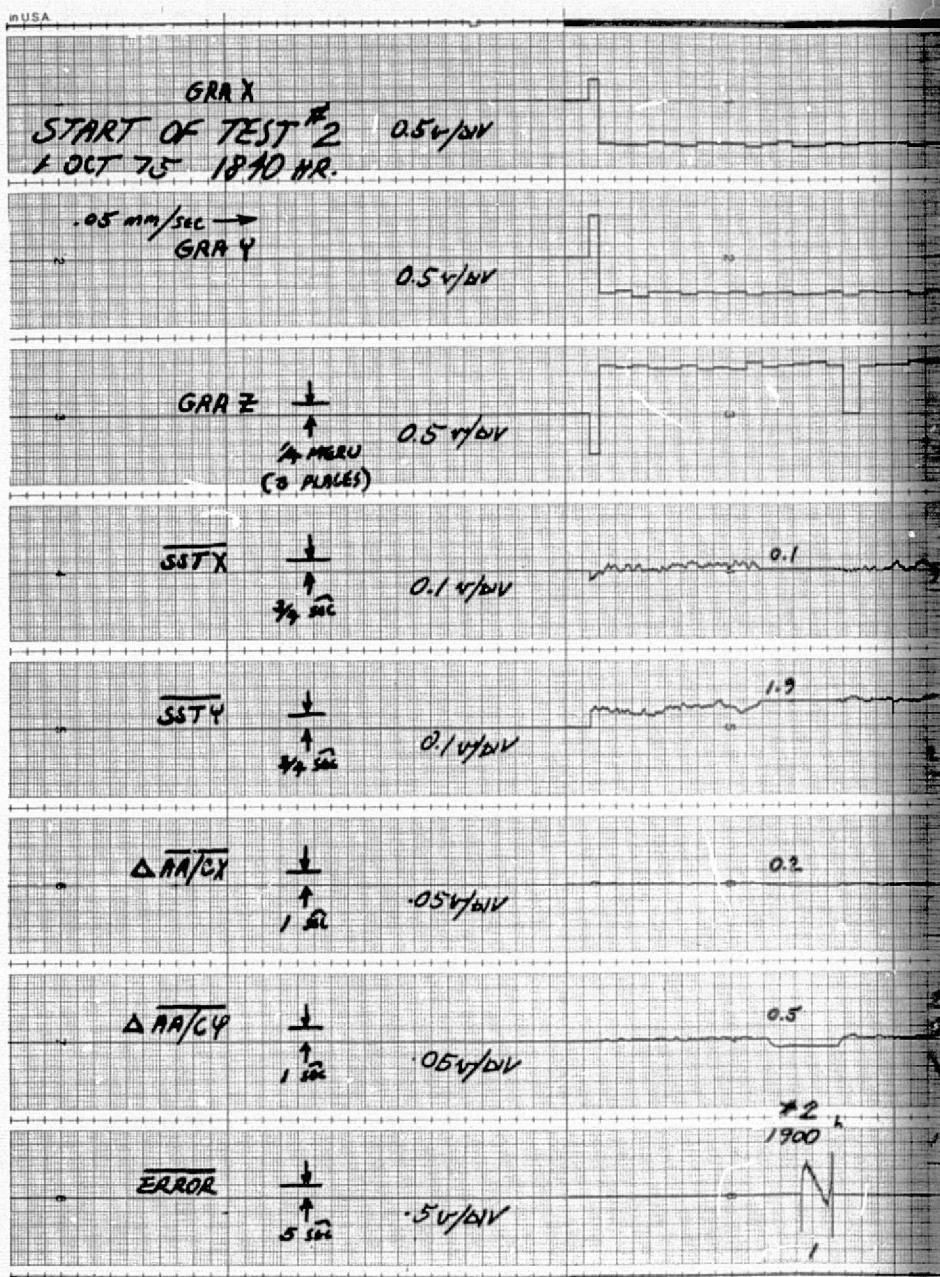
HANNING
POWER BOOST FACTOR 1
DATA REJECTION SIGMA 2.6900693
REJECTED DATA 0 OF 16264 SAMPLES
DATA ACQUISITION DATE 8/10/73

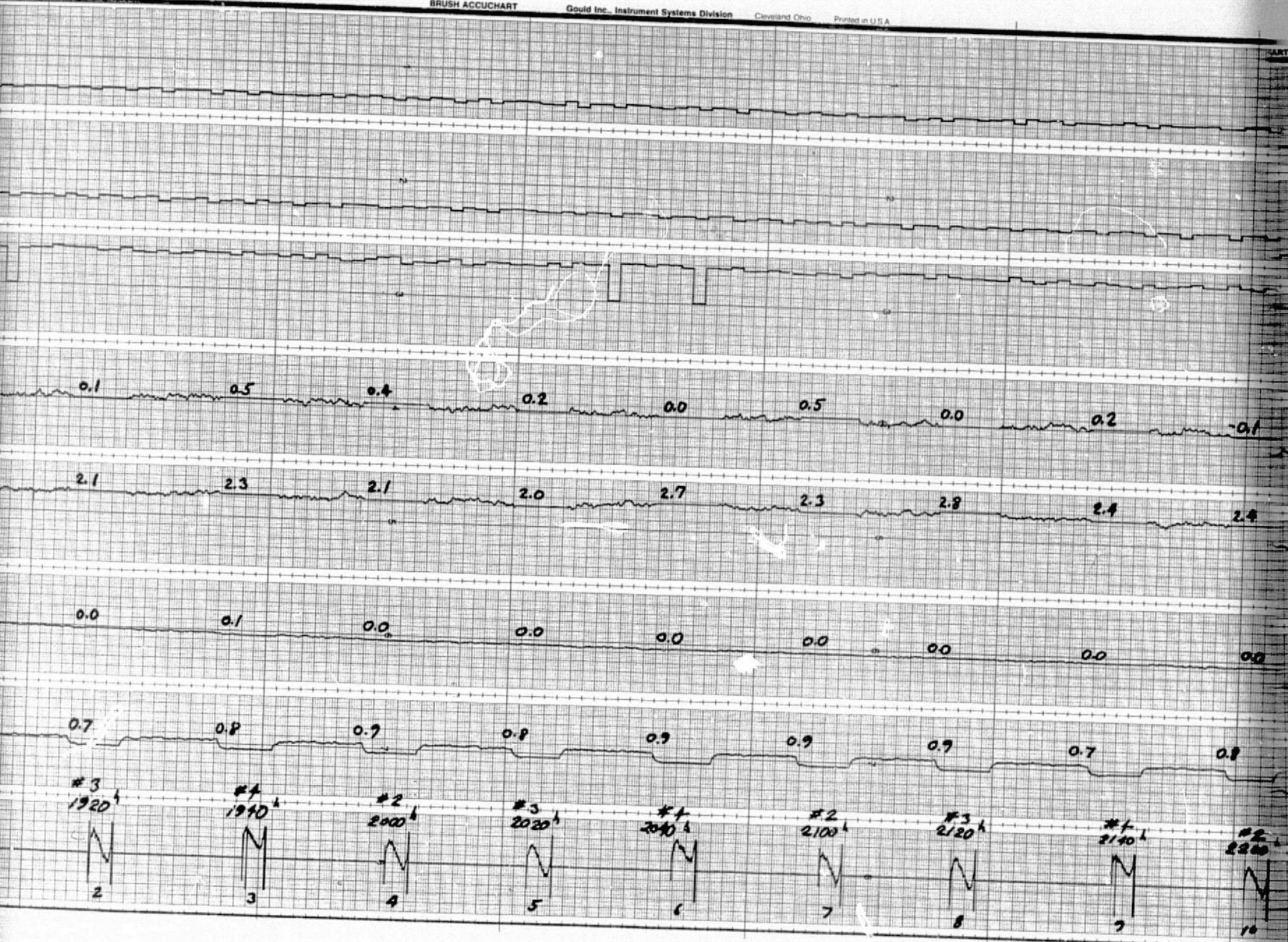
FIGURE 18

APPENDIX D

REAL TIME DISGNOSTIC DATA

~~ROLLOUT FRAME~~





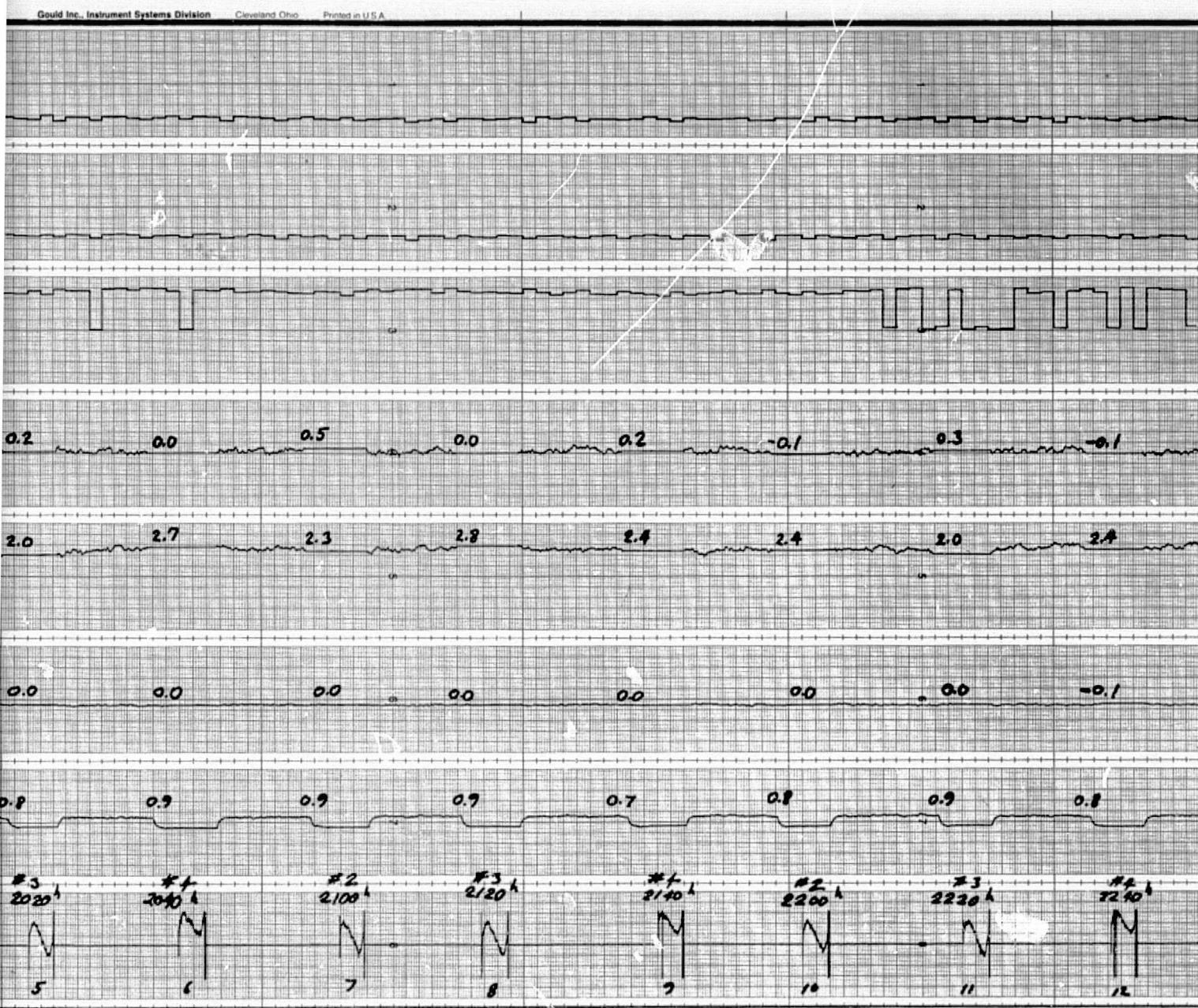


Figure D-1. Strapdown System Test Run No. 1

FOLDOUT FRAME

BRUSH ACCUCHART

Gould Inc., Instrument Systems Division

Cleveland, Ohio

Printed in U.S.A.

START OF TEST #3
3 OCT 75 1990 NR

.5 v/div $\frac{1}{4}$ sec GRAY
 $\frac{1}{4}$ sec

-0.5 mV/sec \rightarrow

.5 v/div $\frac{1}{4}$ sec GRAY
 $\frac{1}{4}$ sec

.5 v/div $\frac{1}{4}$ sec GRAY
 $\frac{1}{4}$ sec

.1 v/div $\frac{1}{4}$ sec SSTX
 $\frac{1}{4}$ sec

.1 v/div $\frac{1}{4}$ sec SSTY
 $\frac{1}{4}$ sec

.05 v/div $\frac{1}{4}$ sec RATE
 $\frac{1}{4}$ sec

.05 v/div $\frac{1}{4}$ sec RATE
 $\frac{1}{4}$ sec

.05 v/div $\frac{1}{4}$ sec ERROR
 $\frac{1}{4}$ sec

FOLDOUT FRAME

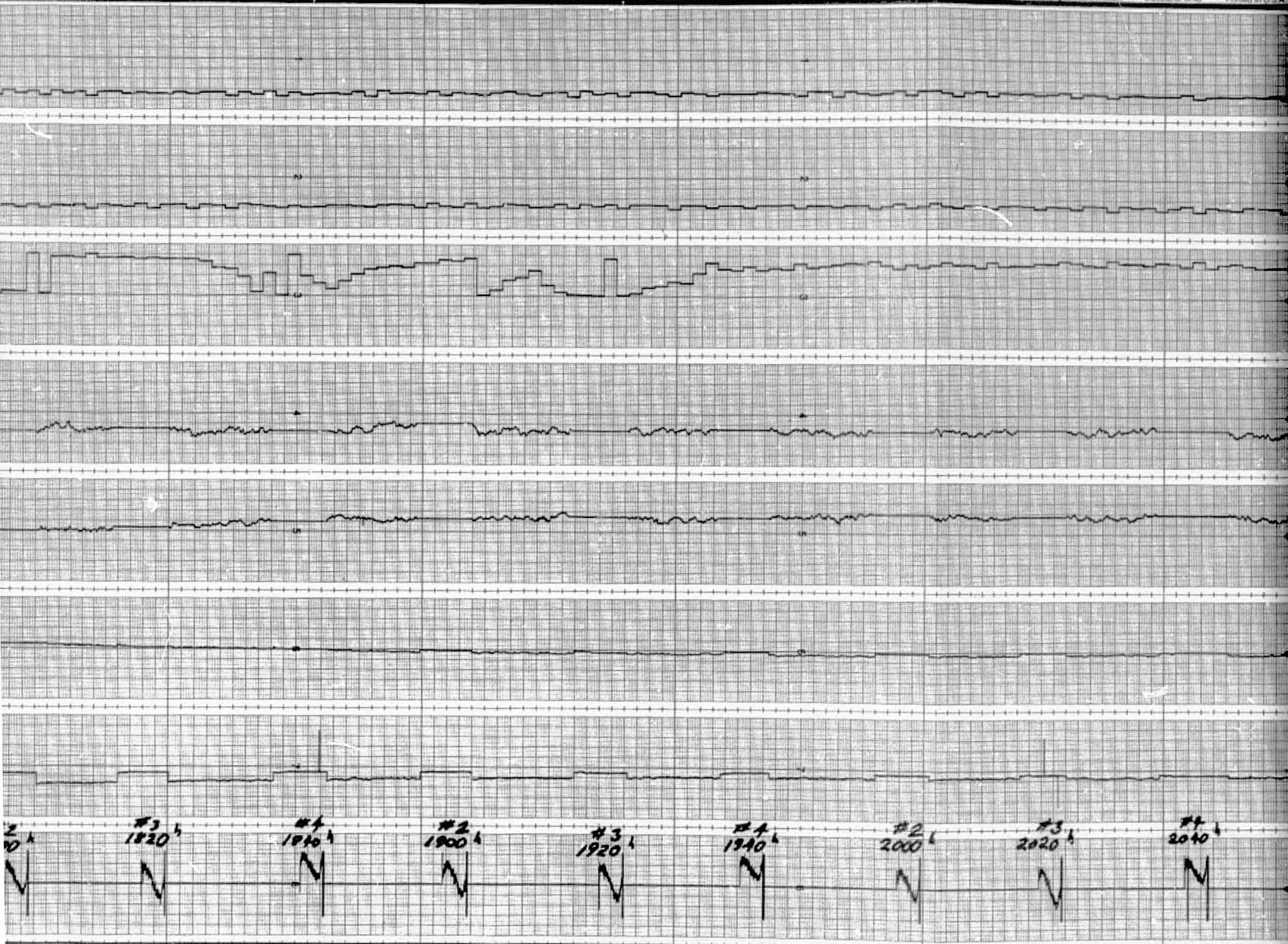
2

BRUSH ACCUCHART

Gould Inc., Instrument Systems Division

Cleveland Ohio

Printed in U.S.A.



START OF TEST #4002.5V/DIV
6 OCT 75 1800 h

0.05 mm/sec →

GRAY .5V/DIV

GRAY .5V/DIV

± 1mm (3 mm)

1/5 sec SSTR .1V/DIV

1/5 sec SSTR .1V/DIV

1/5 sec RR/EX .05 V/DIV

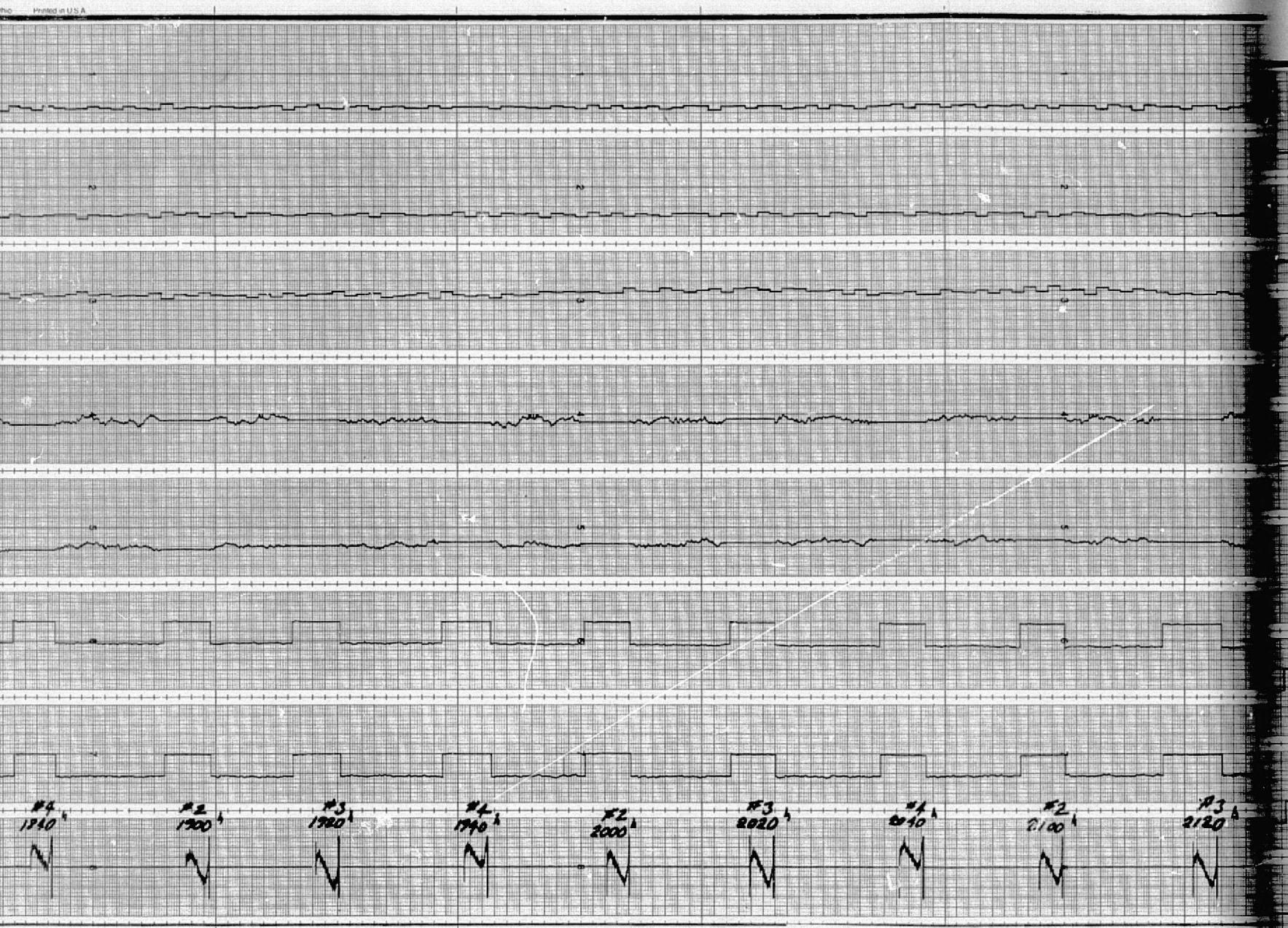
1/5 sec RR/EX .05 V/DIV

1/5 sec ERROR .5V/DIV

#3
1820

FOLDOUT FRAME

K-4



FOLDOUT FRAME 2

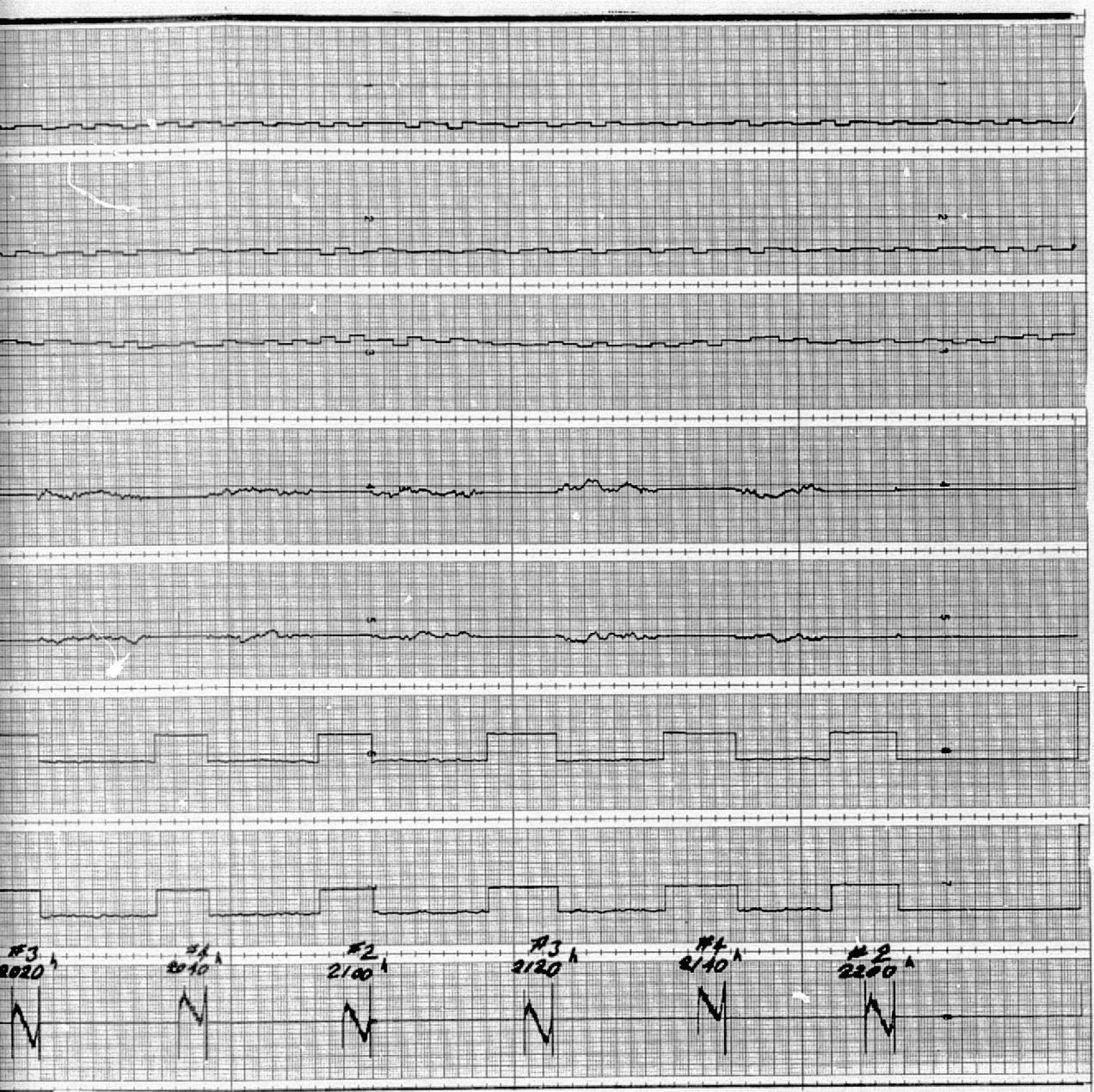


Figure D-3. Strapdown System
Test Run No. 3

D-4

FOLDOUT FRAME 3

START OF TEST #5 GRAY .5v/DIV
8 OCT 75 1625 HR

0.05 mm/sec →

GRAY .5v/DIV

GRAY .5v/DIV

0.25 MEAN
(2 PLATES)
SST X .1v/DIV

3/4 in
SST Y .1v/DIV

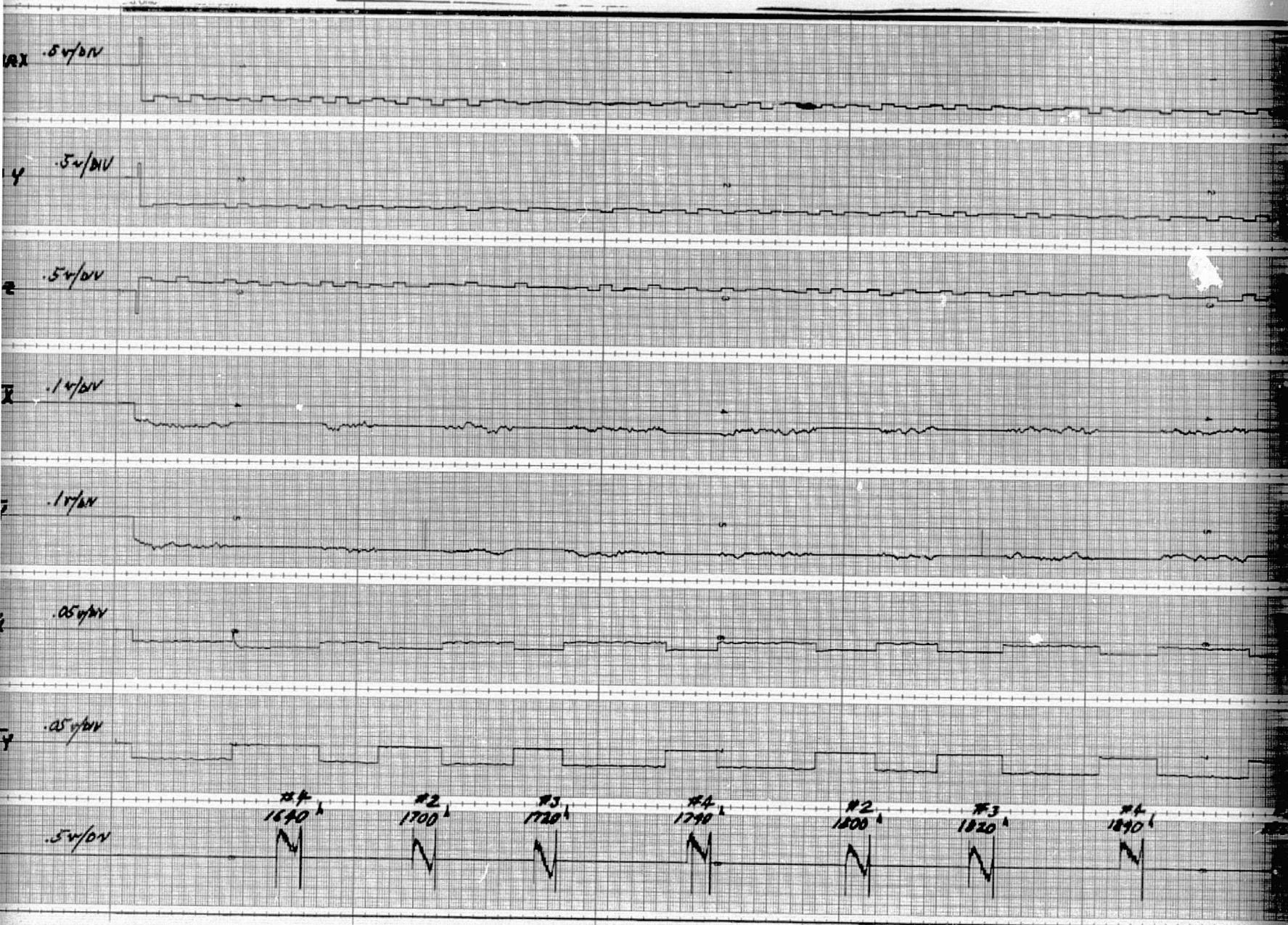
1/2 in
ΔRAY/X .05v/DIV

1/2 in
ΔRAY/Y .05v/DIV

1/2 in
E SST X .5v/DIV

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

FOLDOUT FRAM



FOLDOUT FRAME 2

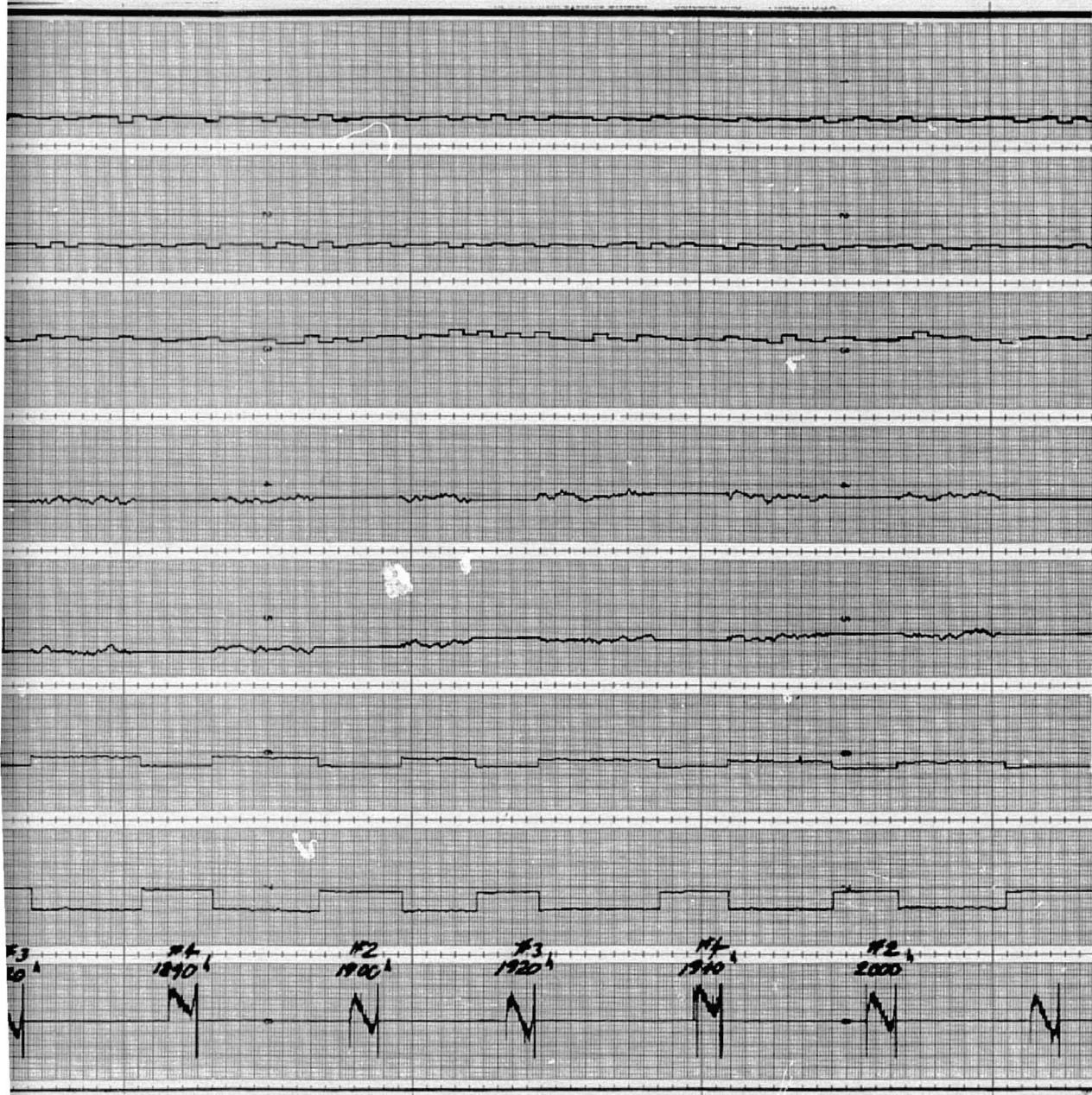


Figure D-4. Strapdown System
Test Run No. 4

START OF TEST #9
6FEB76 1840 HR

GRN X $\frac{1}{1}$
#MEAU

→ .05 MM/MM

GRN Y $\frac{1}{1}$
#MEAU

GRN Z $\frac{1}{1}$
#MEAU

STX $\frac{1}{10}$

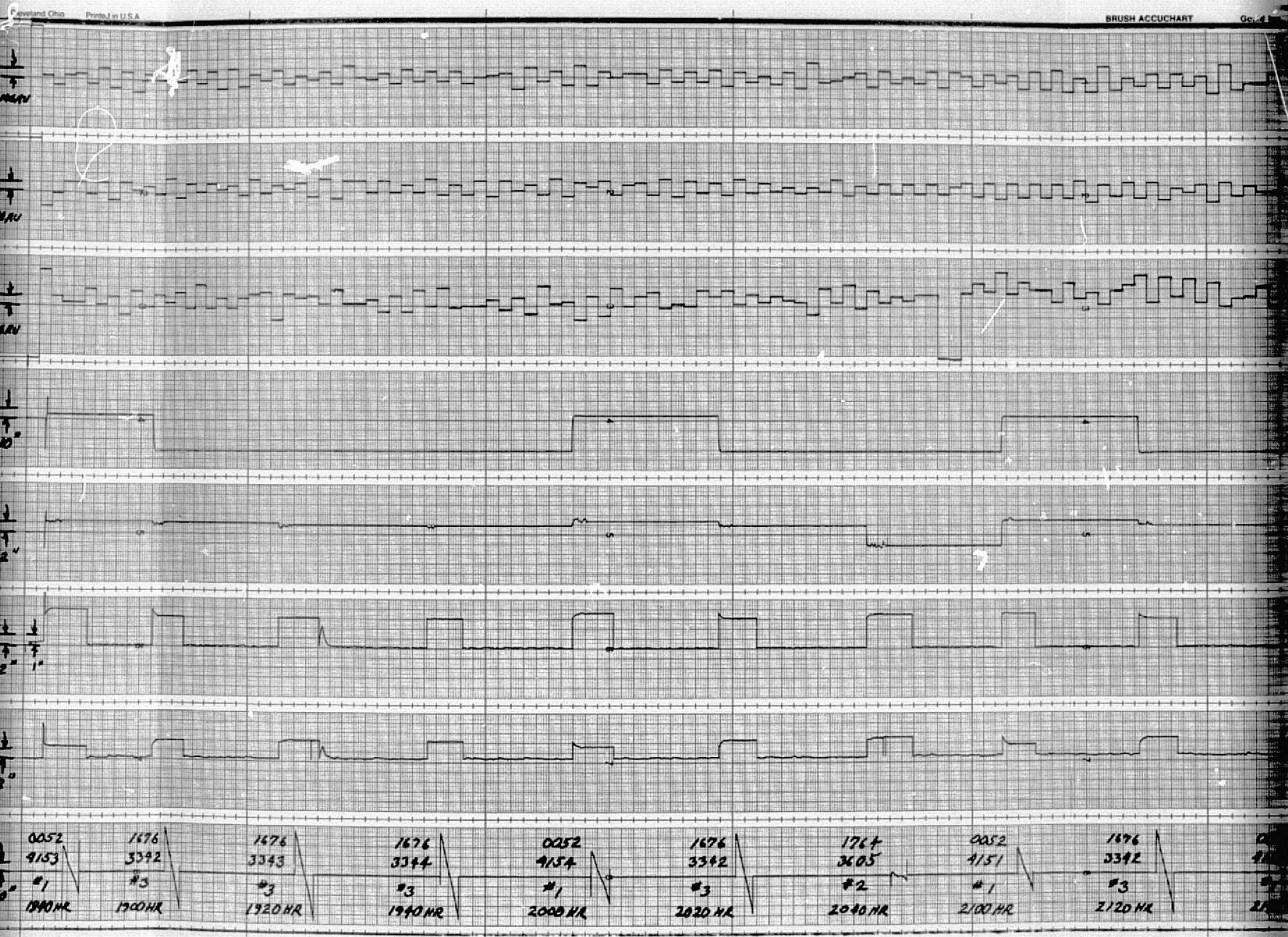
STY $\frac{1}{2}$

RA/CX $\frac{1}{2}$

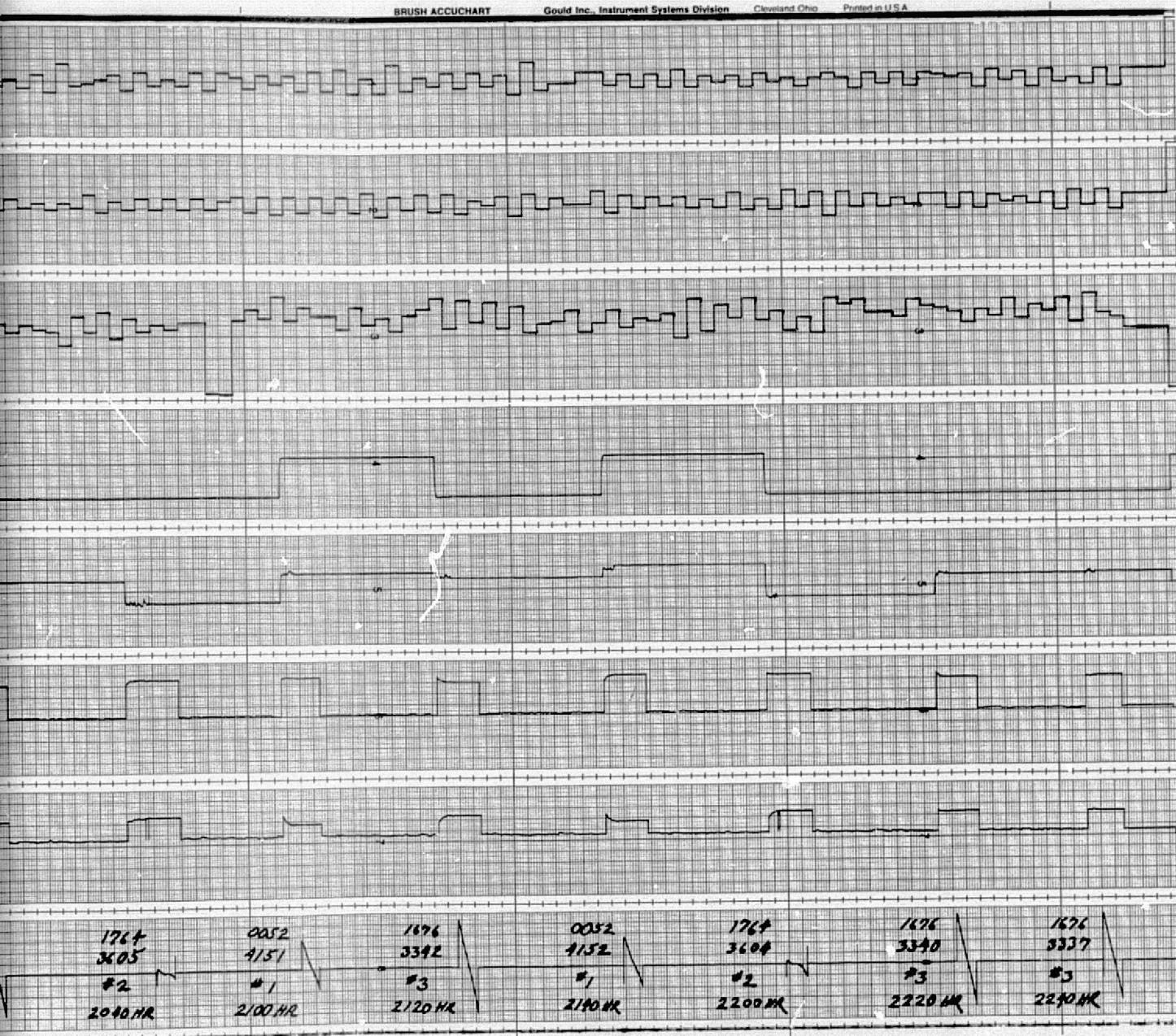
RA/CY $\frac{1}{2}$

ERRDR $\frac{1}{2}$
#1
20" 0052 1676
1940HR 9153 3392 #3
#3 1900HR #3 1920HR

FOLDOFF FRAME



FOLDOUT FRAME



FOLLOW FRAME 3

Figure D-5. Gimbal System
Test Run No. 1

START OF TEST #10_{max} $\frac{1}{4}$
9 FEB 76 1640 HR. $\frac{1}{4}$ $\frac{1}{4}$

05 mm/sec \rightarrow

GRA Y $\frac{1}{4}$
 $\frac{1}{4}$ sec

GRA Z $\frac{1}{4}$
 $\frac{1}{4}$ sec

S7X $\frac{1}{4}$
 $\frac{1}{4}$ sec

S7Y $\frac{1}{4}$
 $\frac{1}{4}$ sec

RA/CX $\frac{1}{4}$
 $\frac{1}{4}$ sec

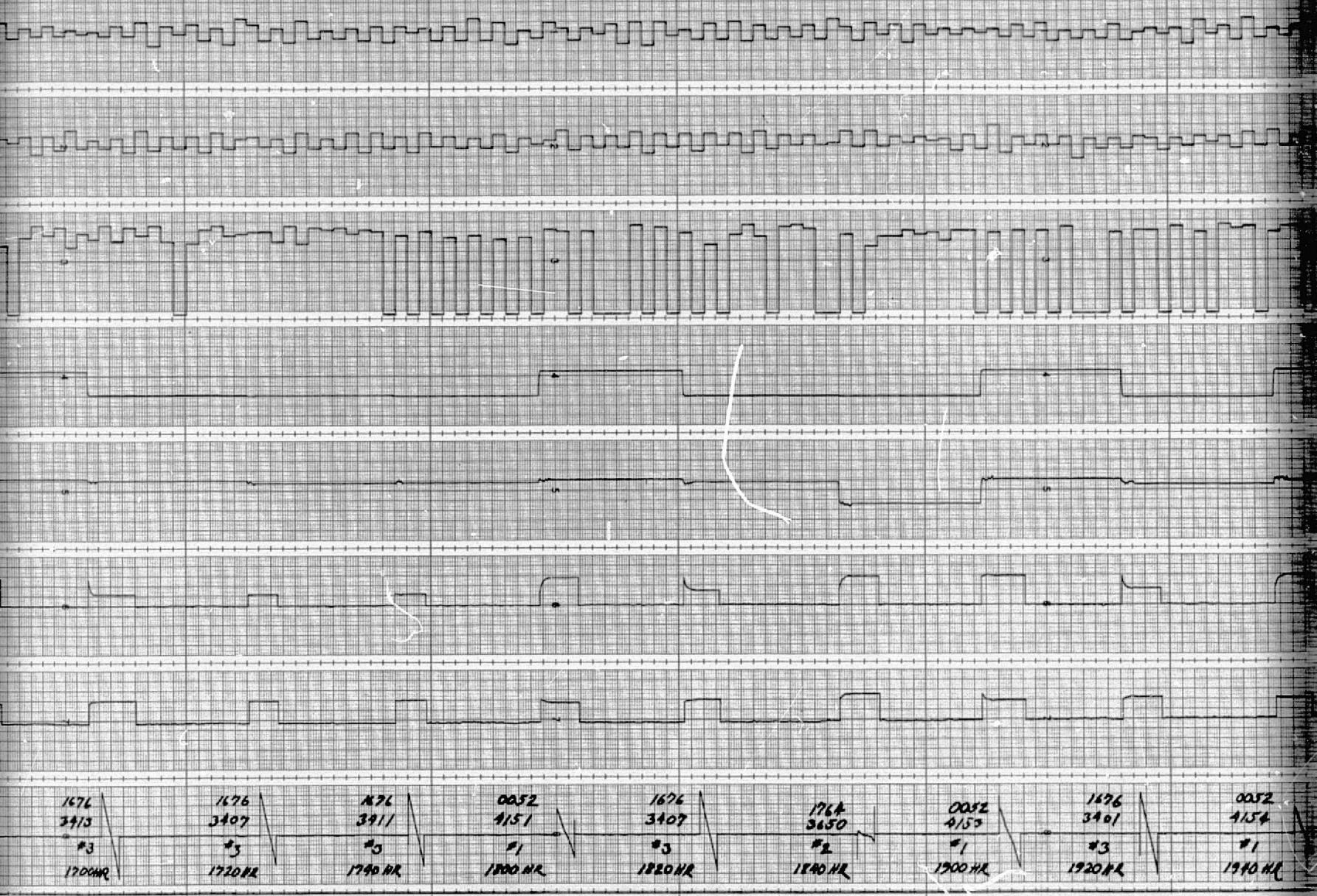
RA/CY $\frac{1}{4}$
 $\frac{1}{4}$ sec

ERROR $\frac{1}{4}$
 $\frac{1}{4}$ sec

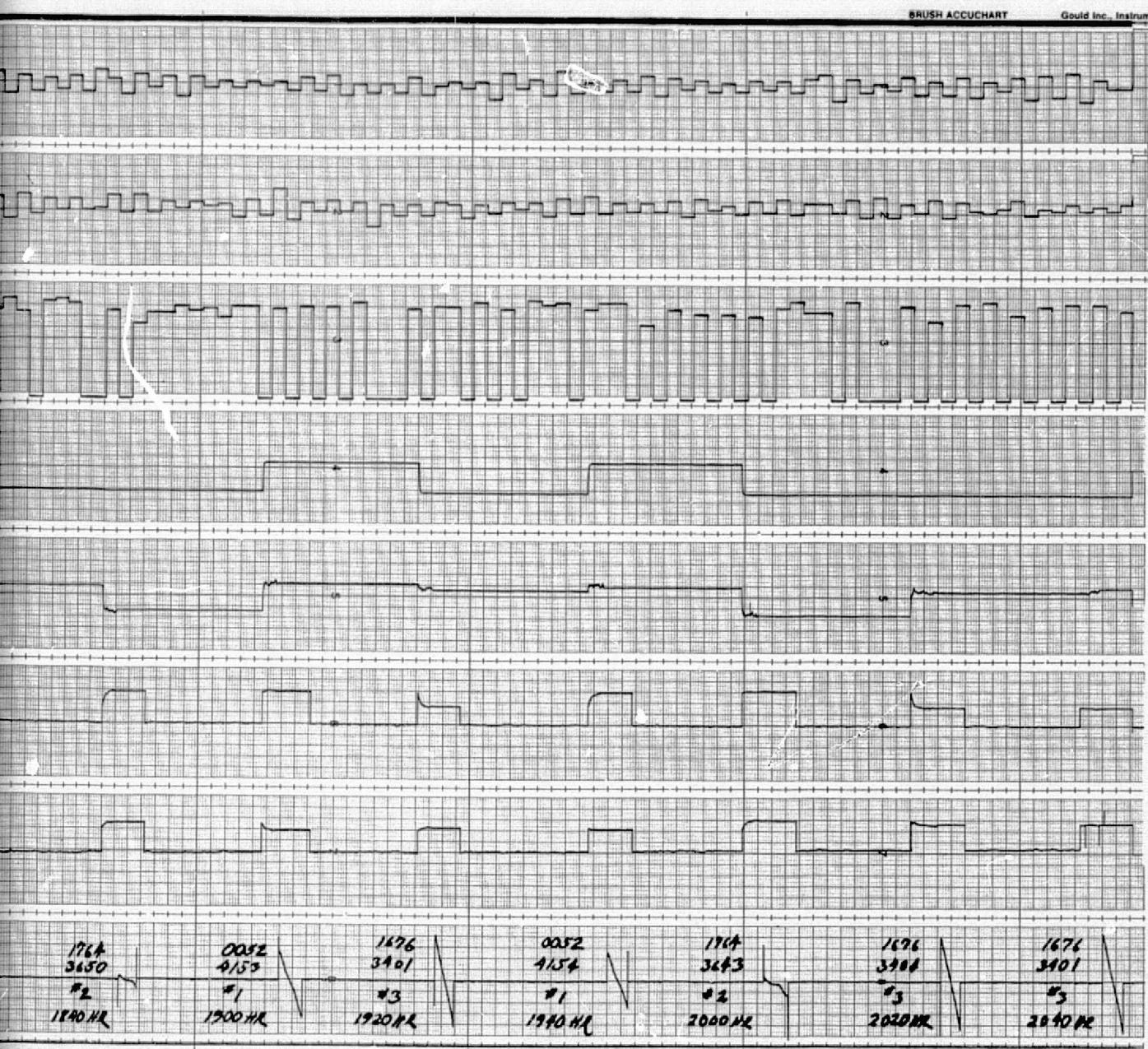
1676
3413
P3
1700HR

1676
3407
P3
1720HR

NO DOUT FRAME



BY TWIT FRAMES



~~FOLDOUT FRAME~~ 3

Figure D-6. Gimbal System
Test Run No. 2

START OF TEST #11
11 FEB 76 1720 HR

GRA X $\frac{1}{1}$
~~5MMU~~

$\sim 0.5 \text{ mm/sec}$

GRA Y $\frac{1}{1}$
~~5MMU~~

"

GRA Z $\frac{1}{1}$
~~5MMU~~

"

STA $\frac{1}{1}$
 $10''$

"

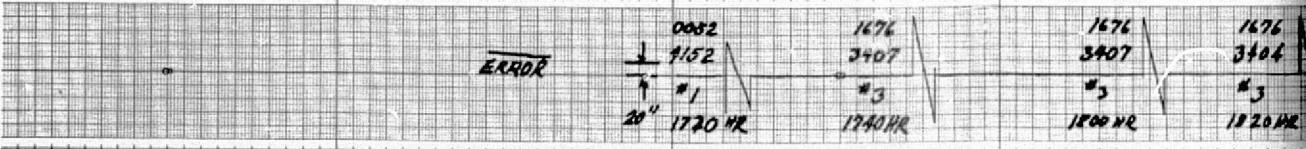
STY $\frac{1}{1}$
 $2''$

"

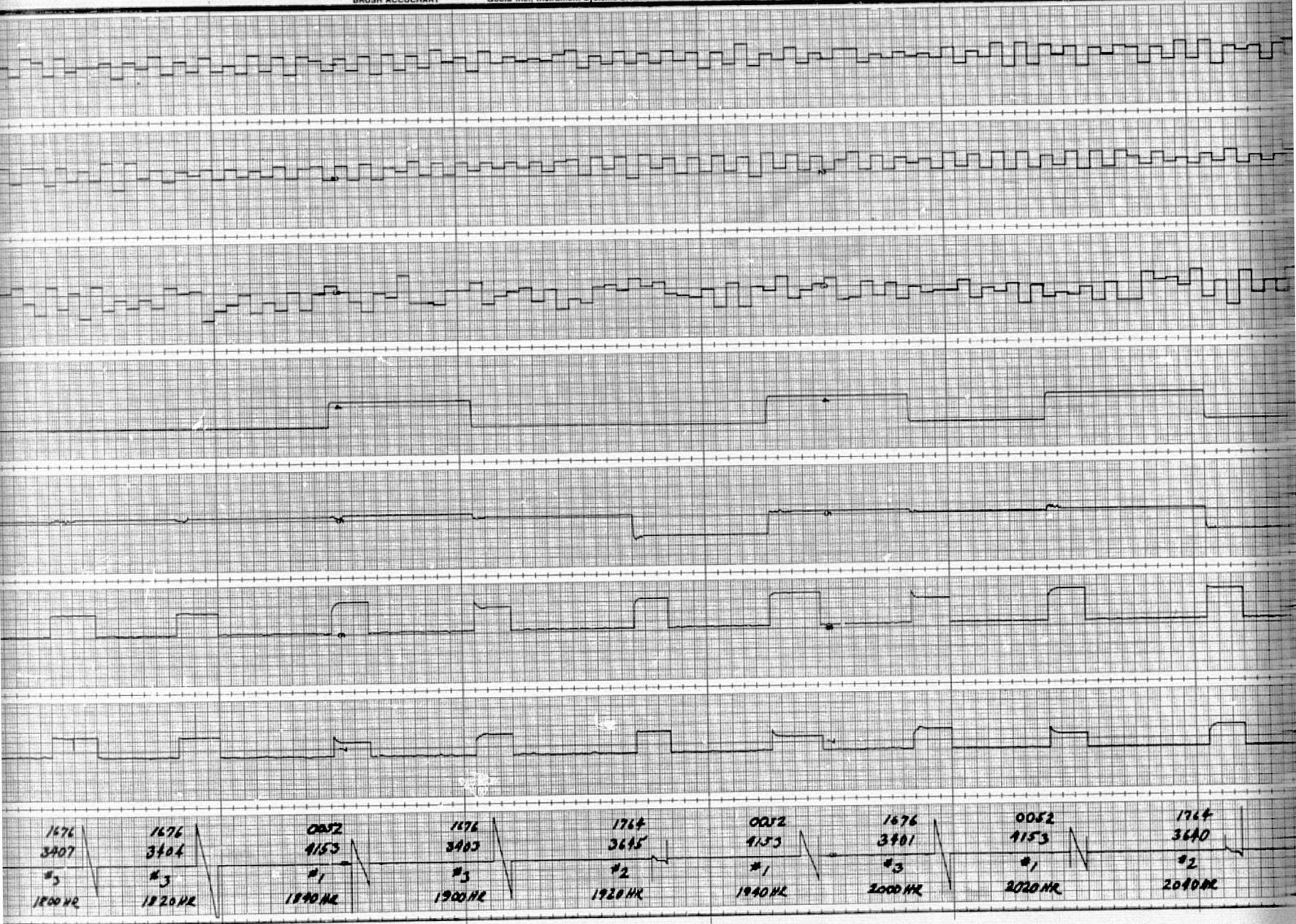
RA/GX $\frac{1}{1}$
 $2''$

"

RA/GY $\frac{1}{1}$
 $2''$



FOLDOUT FRAME



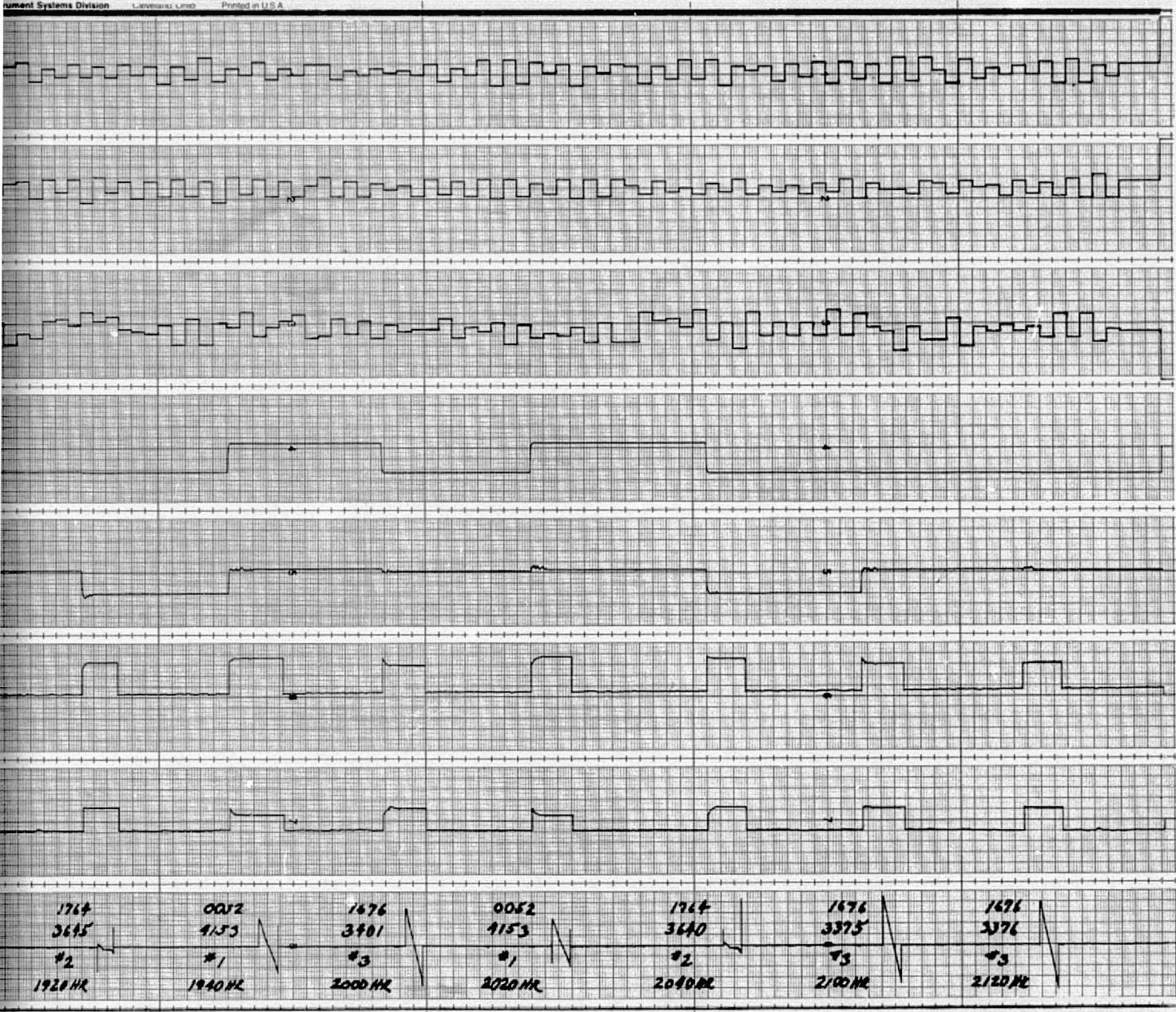


Figure D-7. Gimbal System
Test Run No. 3

START OF TEST #12
16 FEB 76 1720 HR

GEN X $\frac{1}{1}$
 $\frac{f_{NARU}}{1}$

~0.05 mm/sec →

GEN Y $\frac{1}{1}$
 $\frac{f_{NARU}}{1}$

GEN Z $\frac{1}{1}$
 $\frac{f_{NARU}}{1}$

B7Y $\frac{1}{1}$
 $\frac{f_{NARU}}{10^2}$

S7Y $\frac{1}{1}$
 $\frac{2''}{2''}$

RATEX $\frac{1}{1}$
 $\frac{2''}{2''}$

RA/CG $\frac{1}{1}$
 $\frac{2''}{2''}$

ERROR $\frac{1}{1}$
 $\frac{10''}{10''}$

0052
4156

1676
3402

1676
3376

1676
3376

0052
4157

FULLOUT FRAME



FOLDOUT FRAME 2

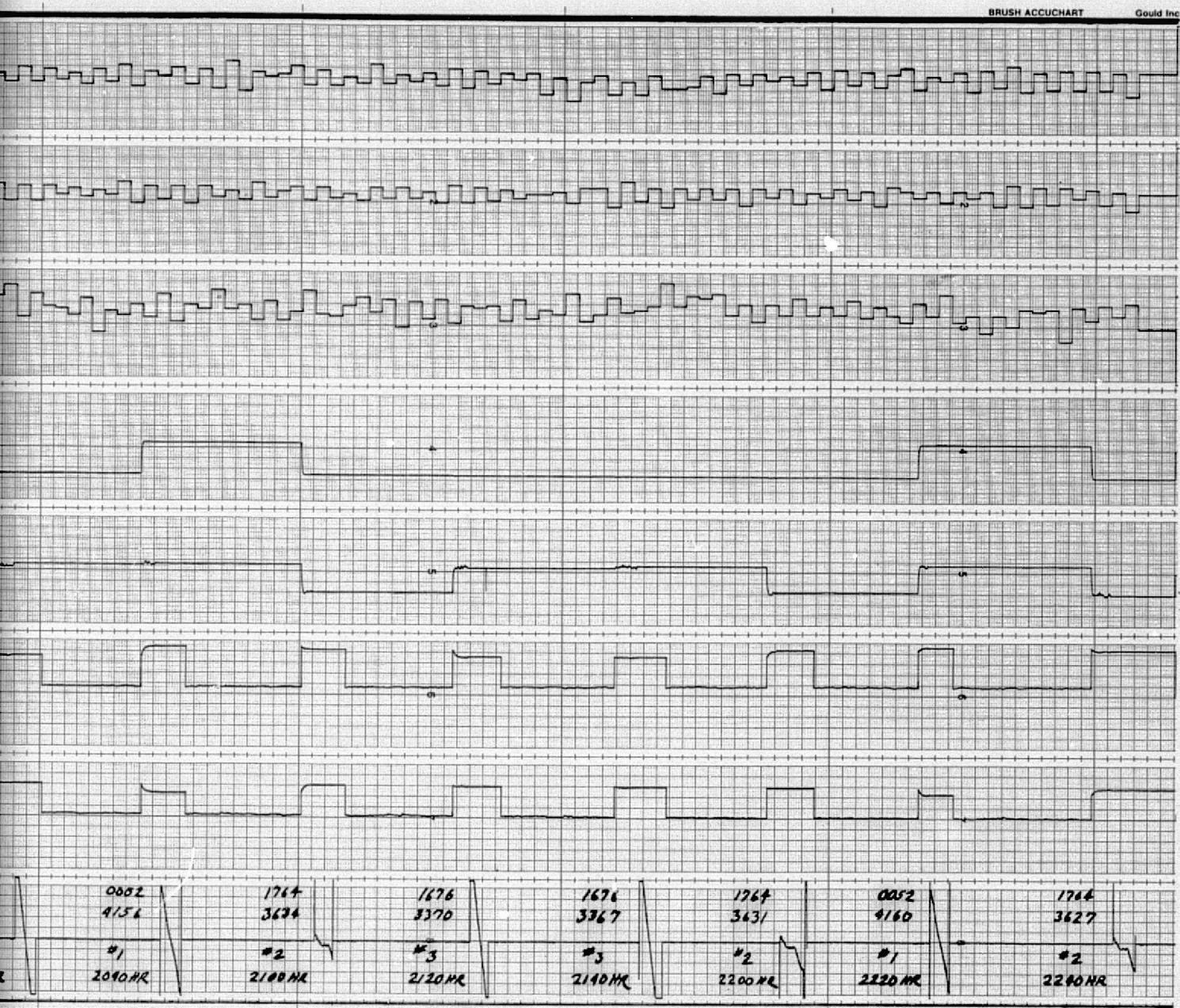


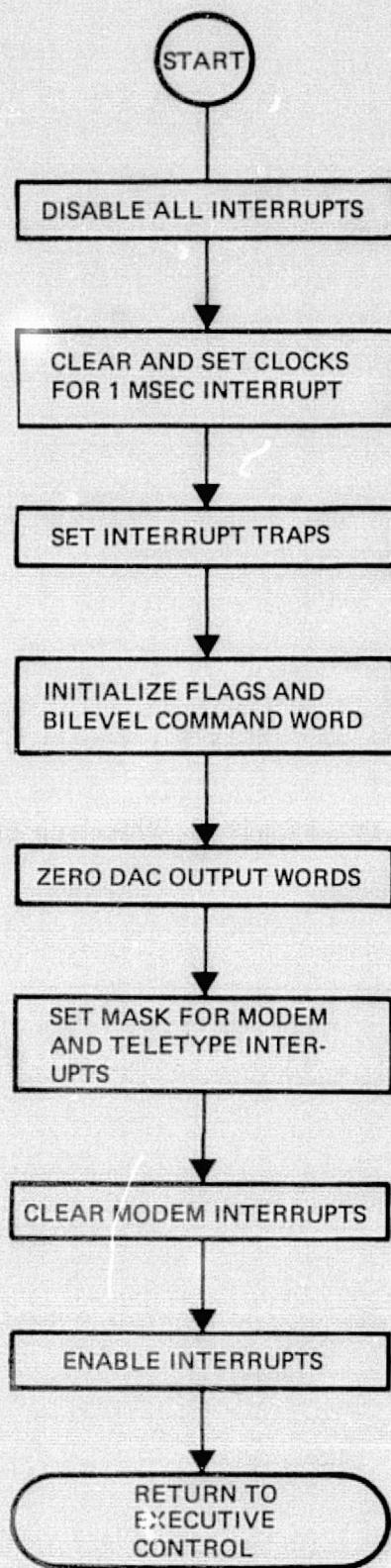
Figure D-8. Gimbal System
Test Run No. 4

FOLDOUT FRAME 3

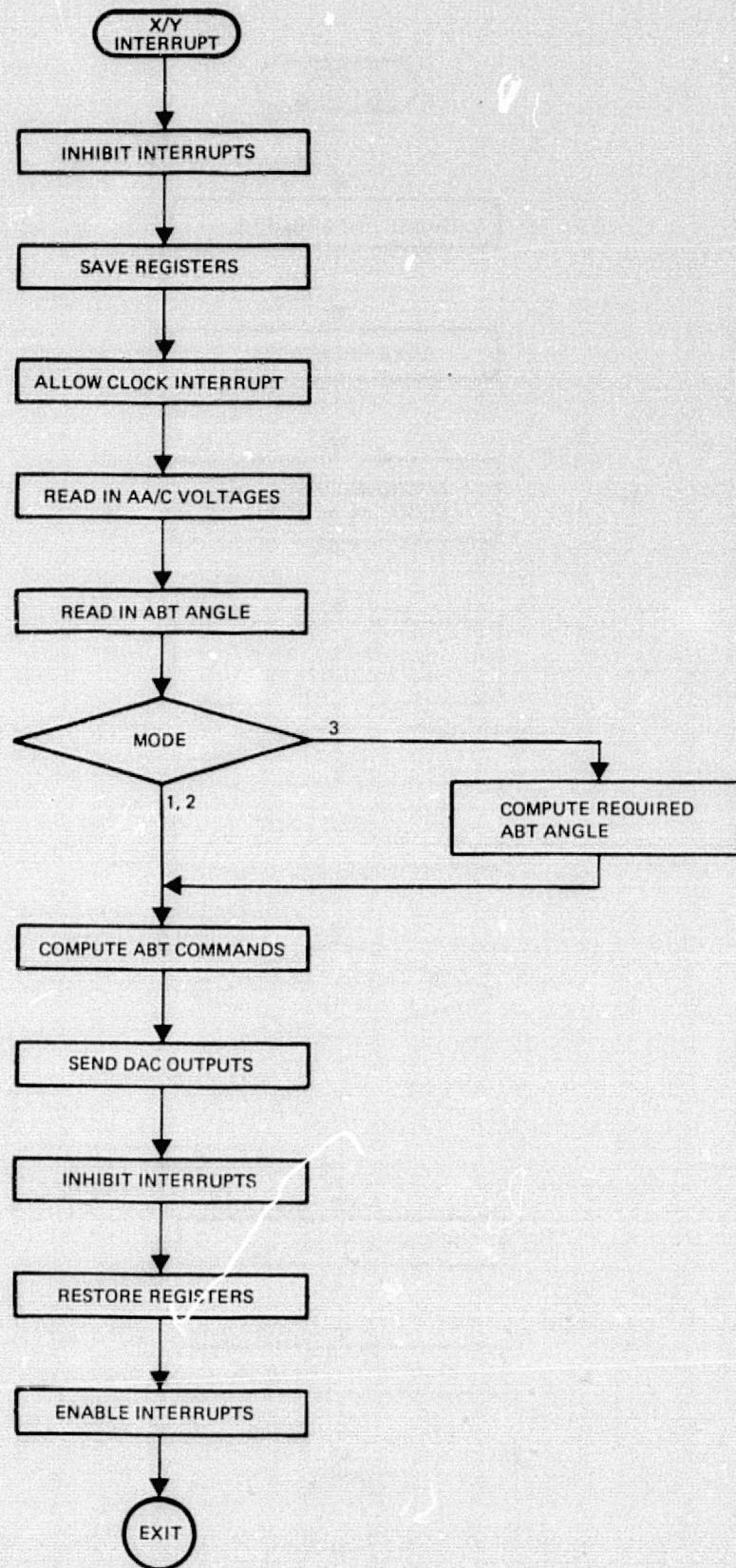
D-9

APPENDIX E

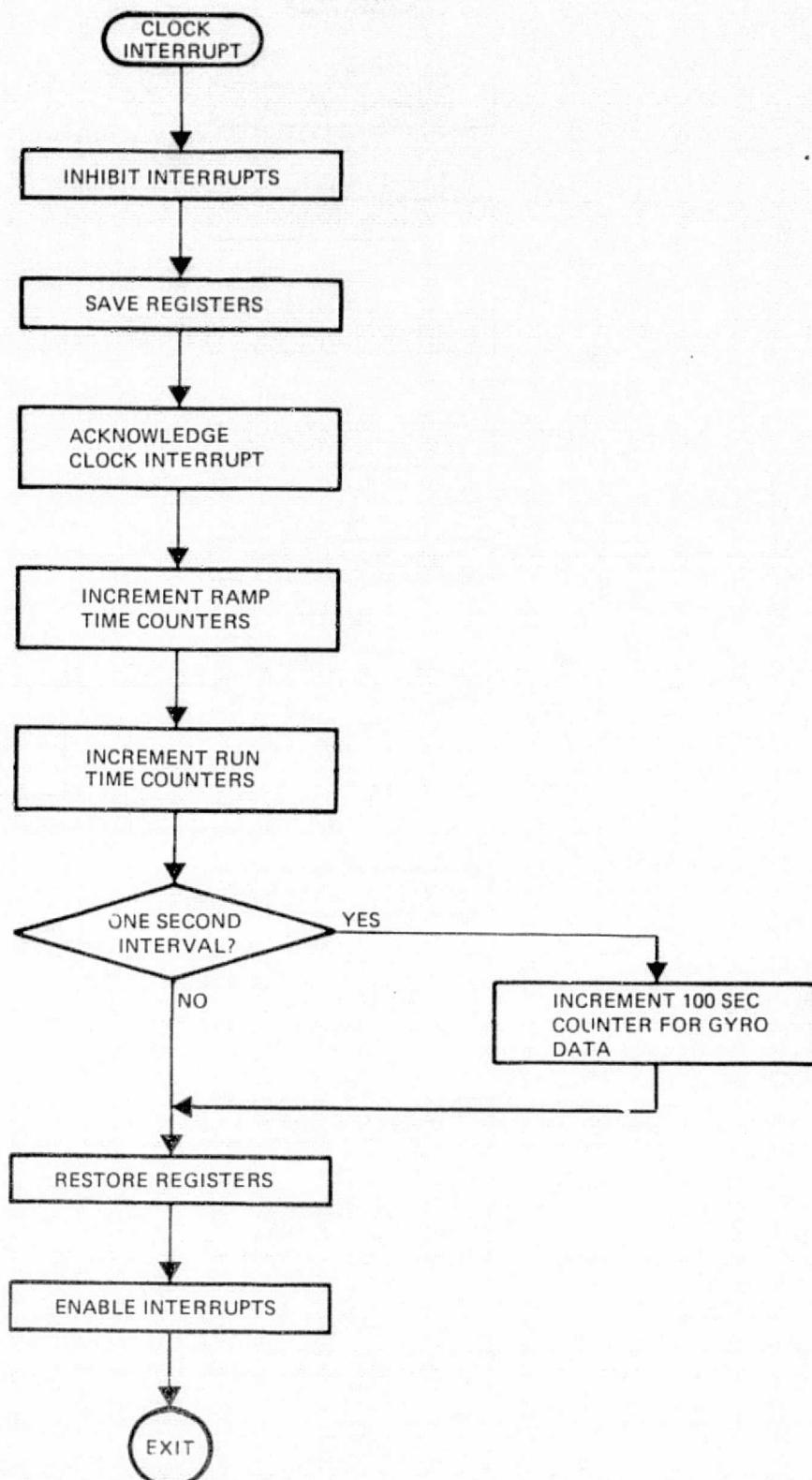
FLOW DIAGRAMS OF LABORATORY COMPUTER PROGRAMS



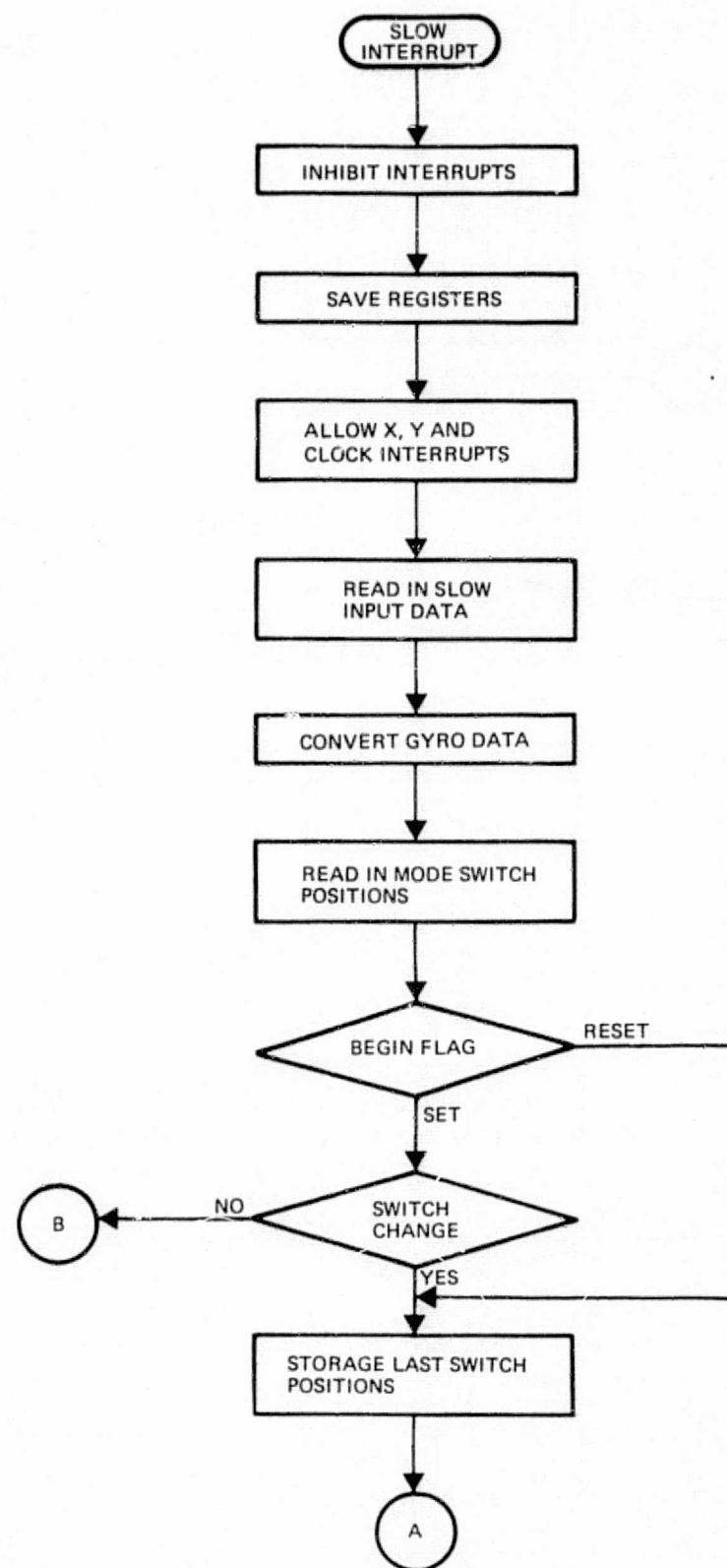
SUE Program Flow Charts (1 of 7)



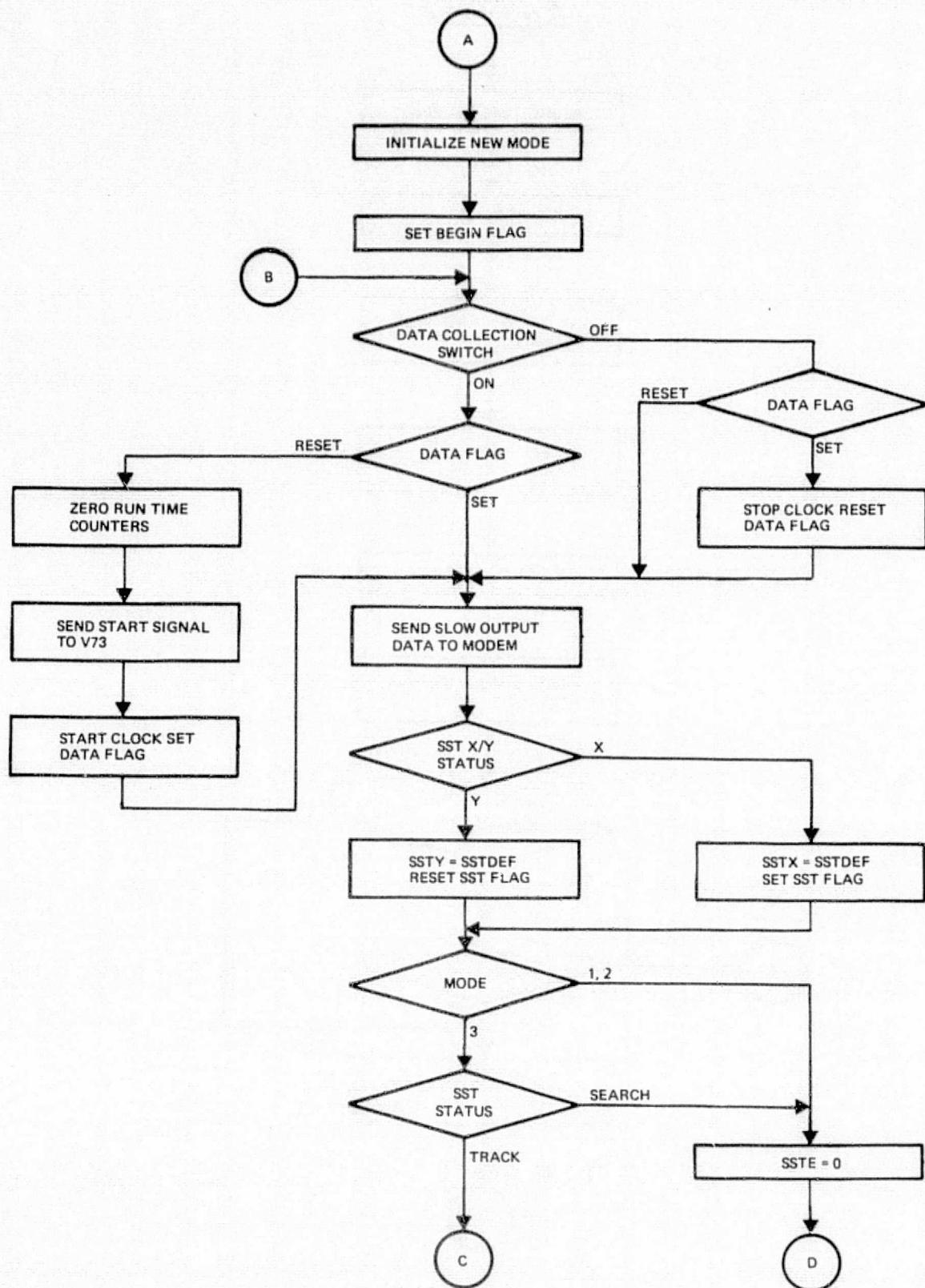
SUE Program Flow Charts (2 of 7)



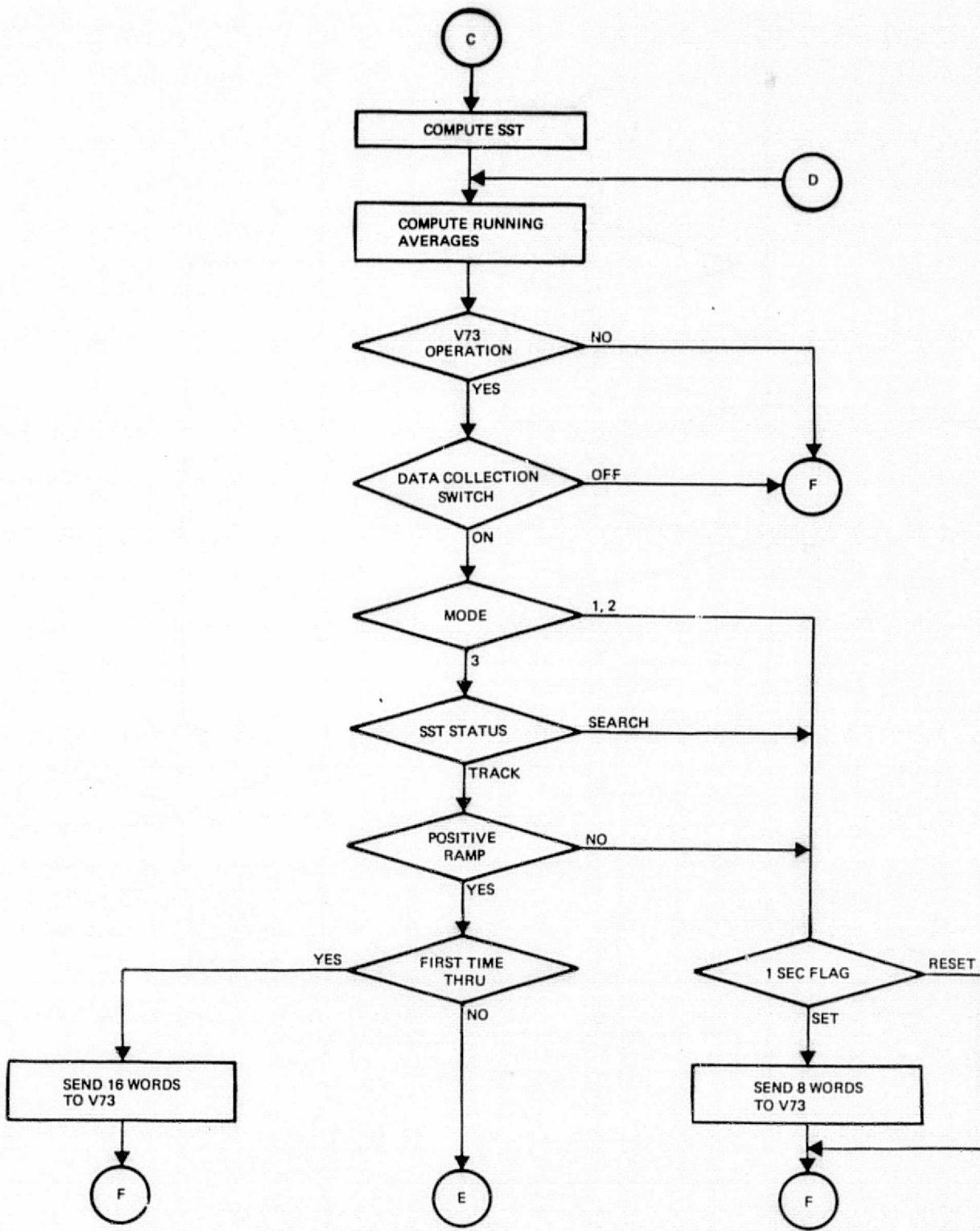
SUE Program Flow Charts (3 of 7)



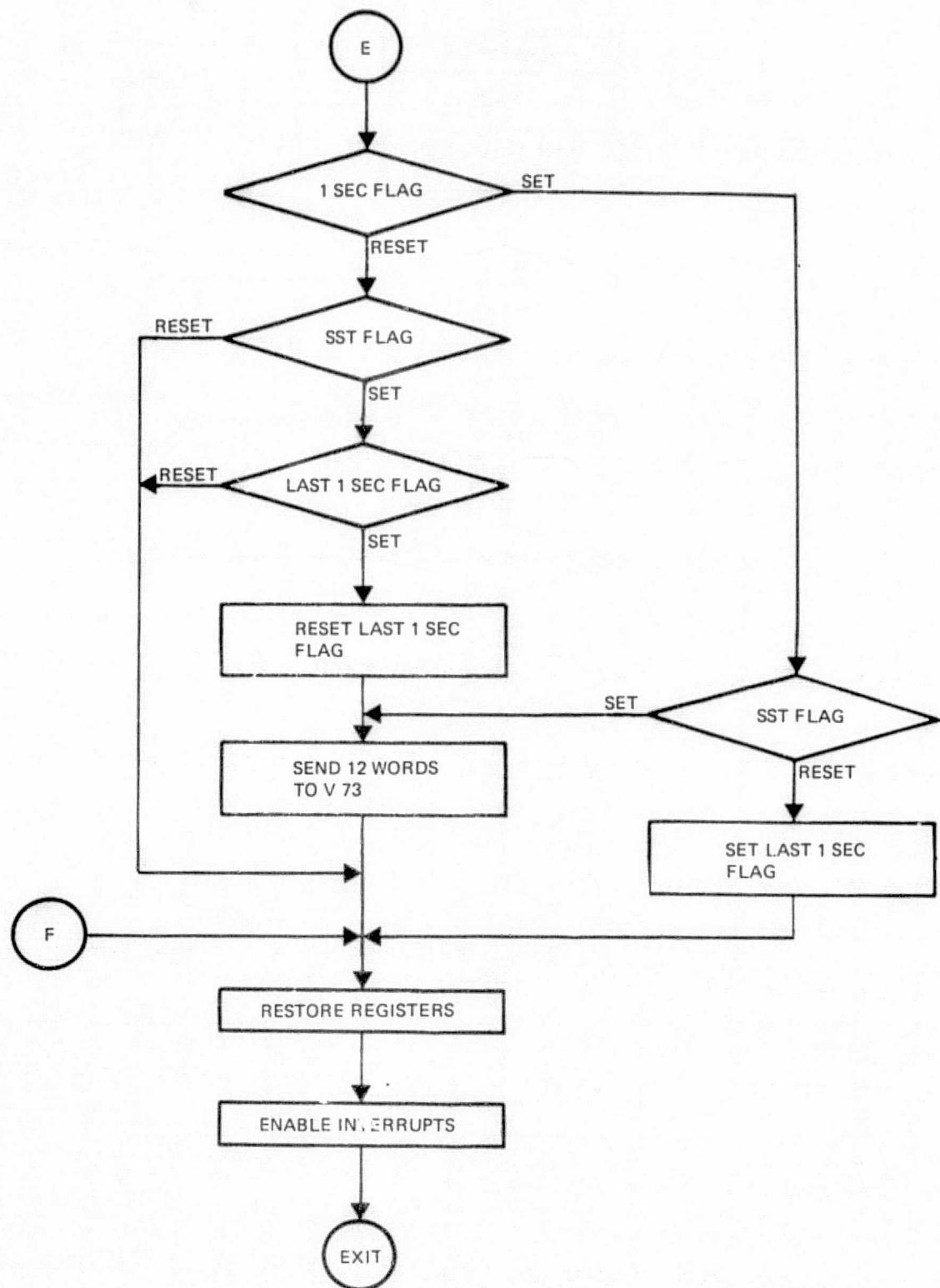
SUE Program Flow Charts (4 of 7)



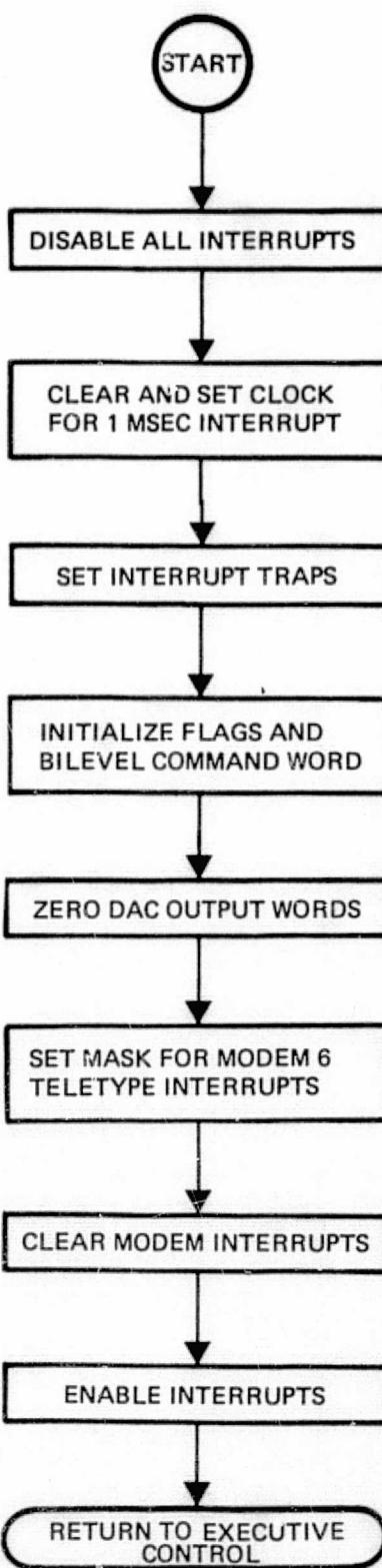
SUE Program Flow Charts (5 of 7)



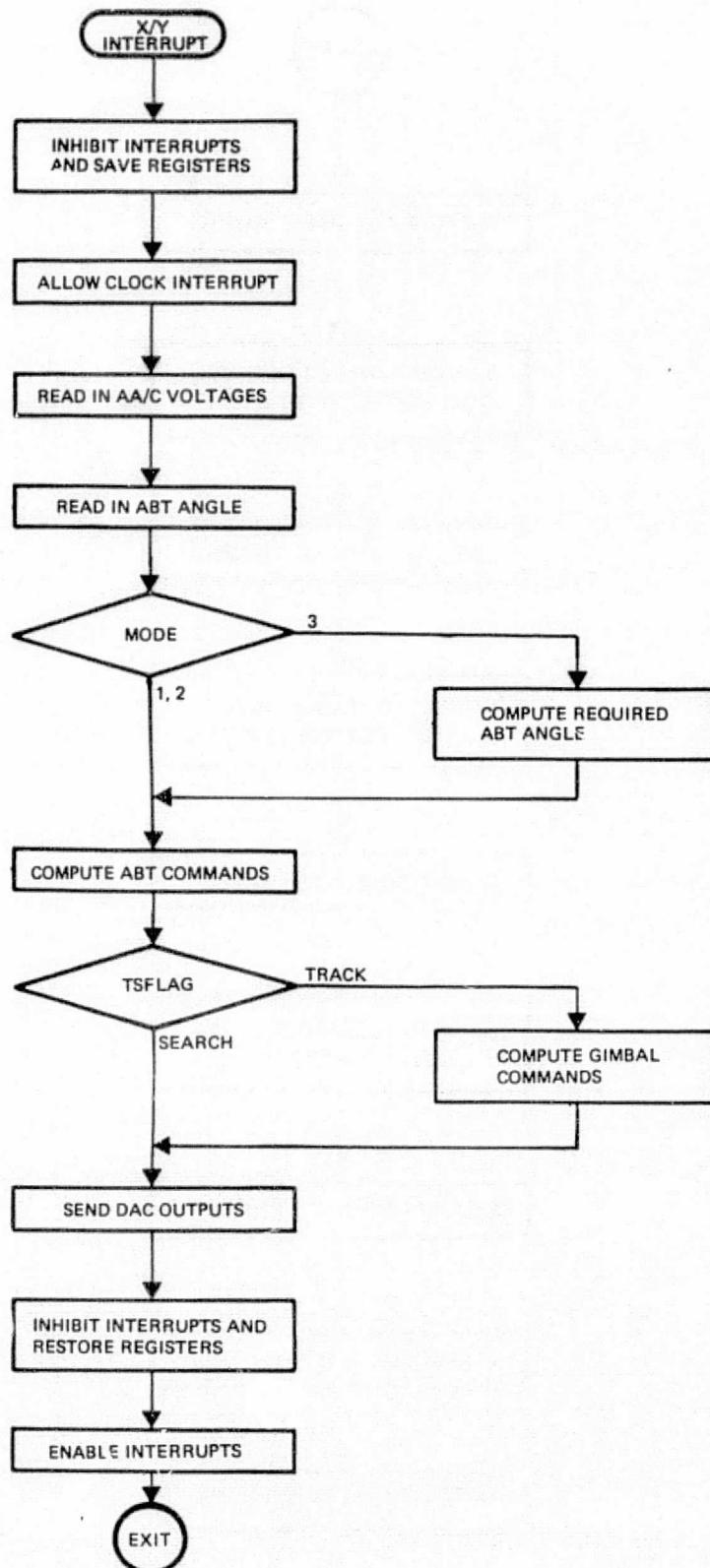
SUE Program Flow Charts (6 of 7)



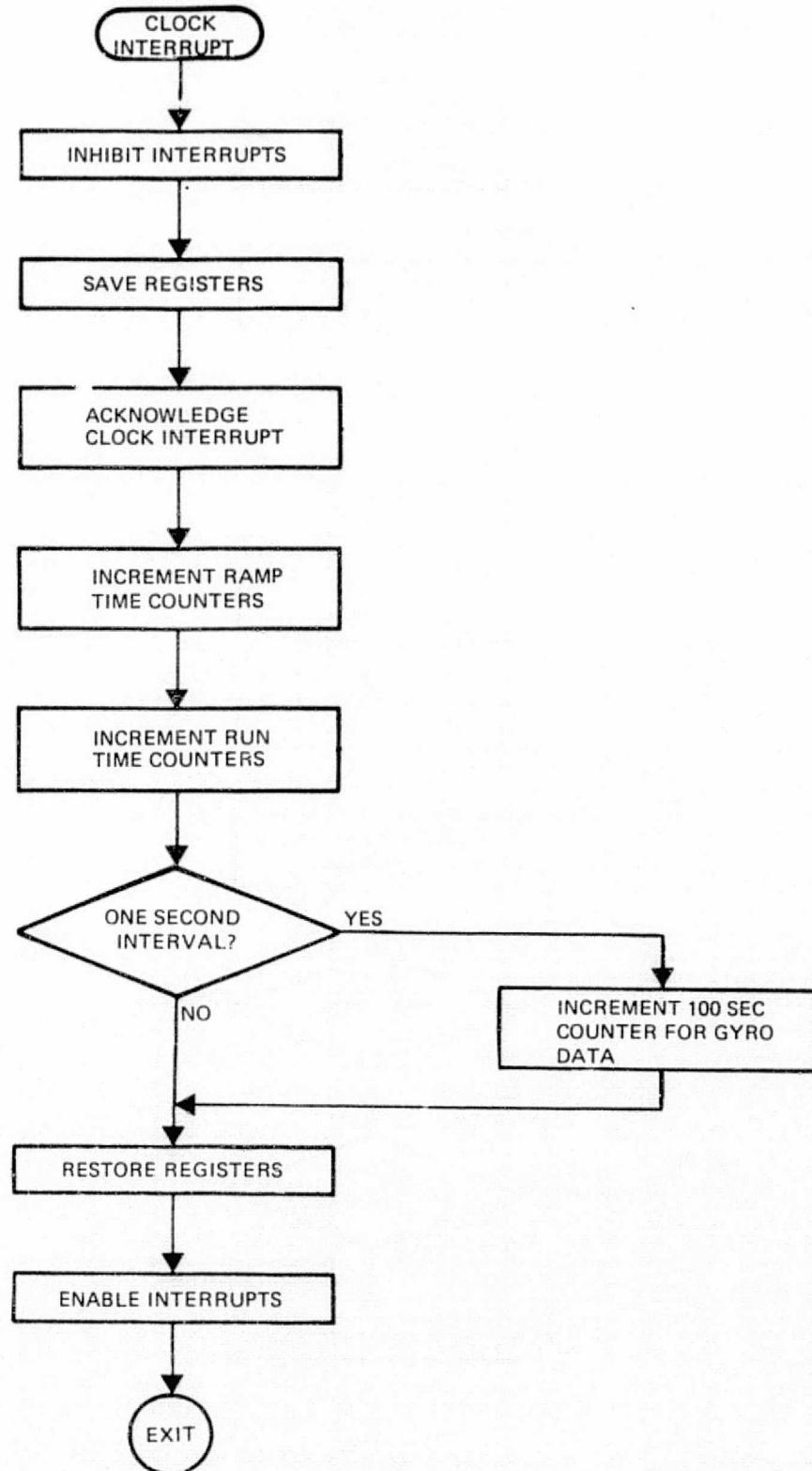
SUE Program Flow Charts (7 of 7)



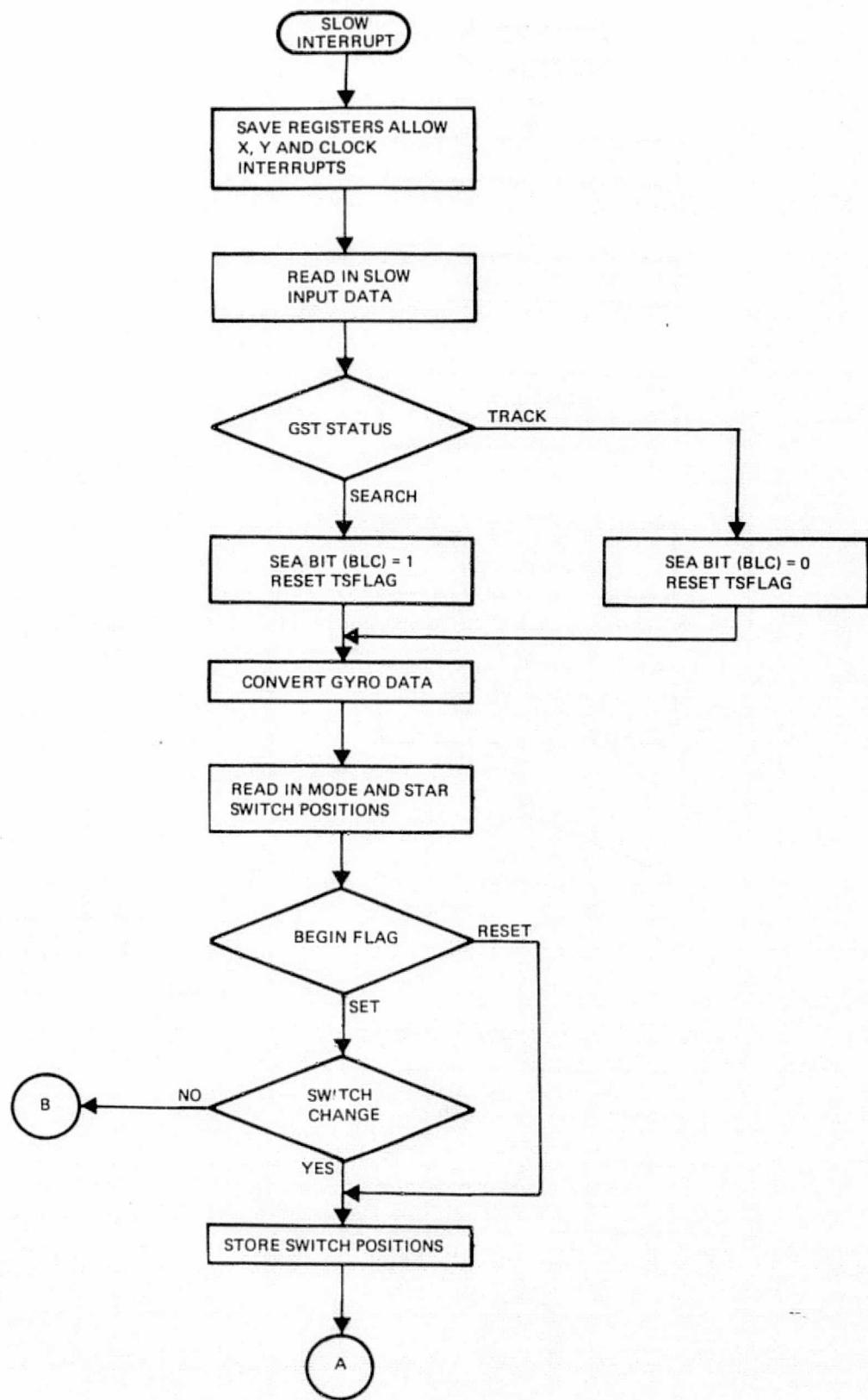
GWEN Program Flow Charts (1 of 7)



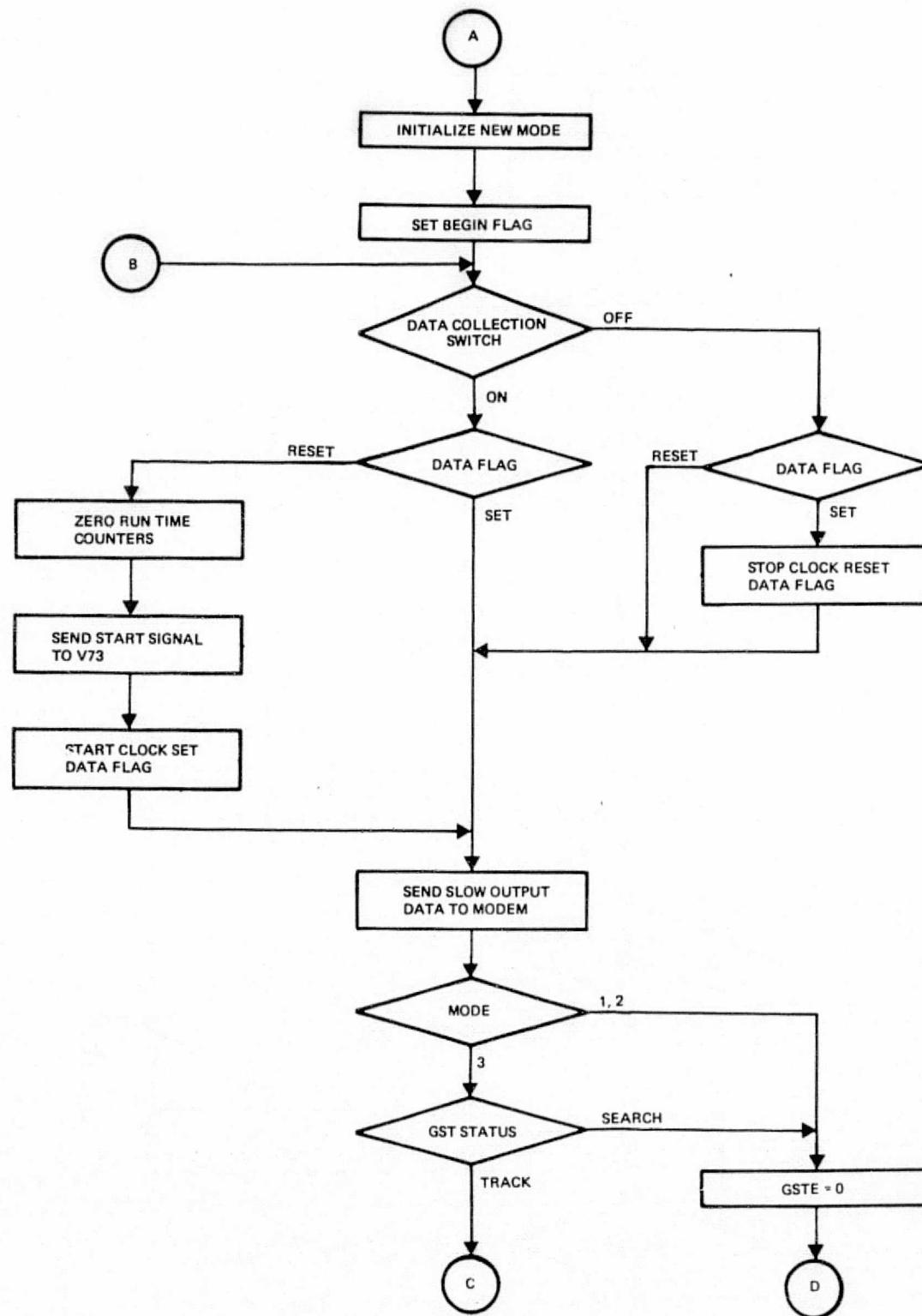
GWEN Program Flow Charts (2 of 7)



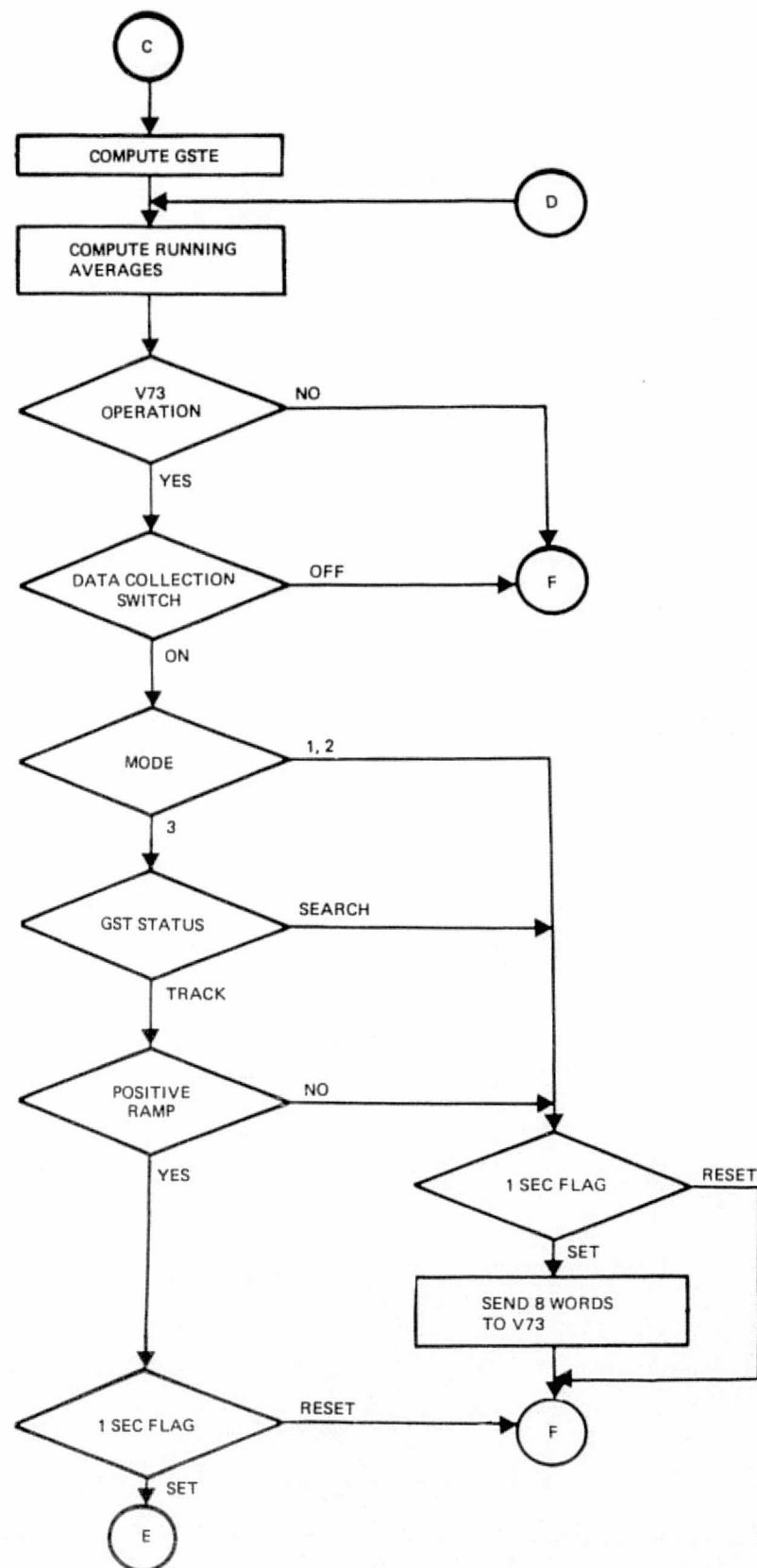
GWEN Program Flow Charts (3 of 7)



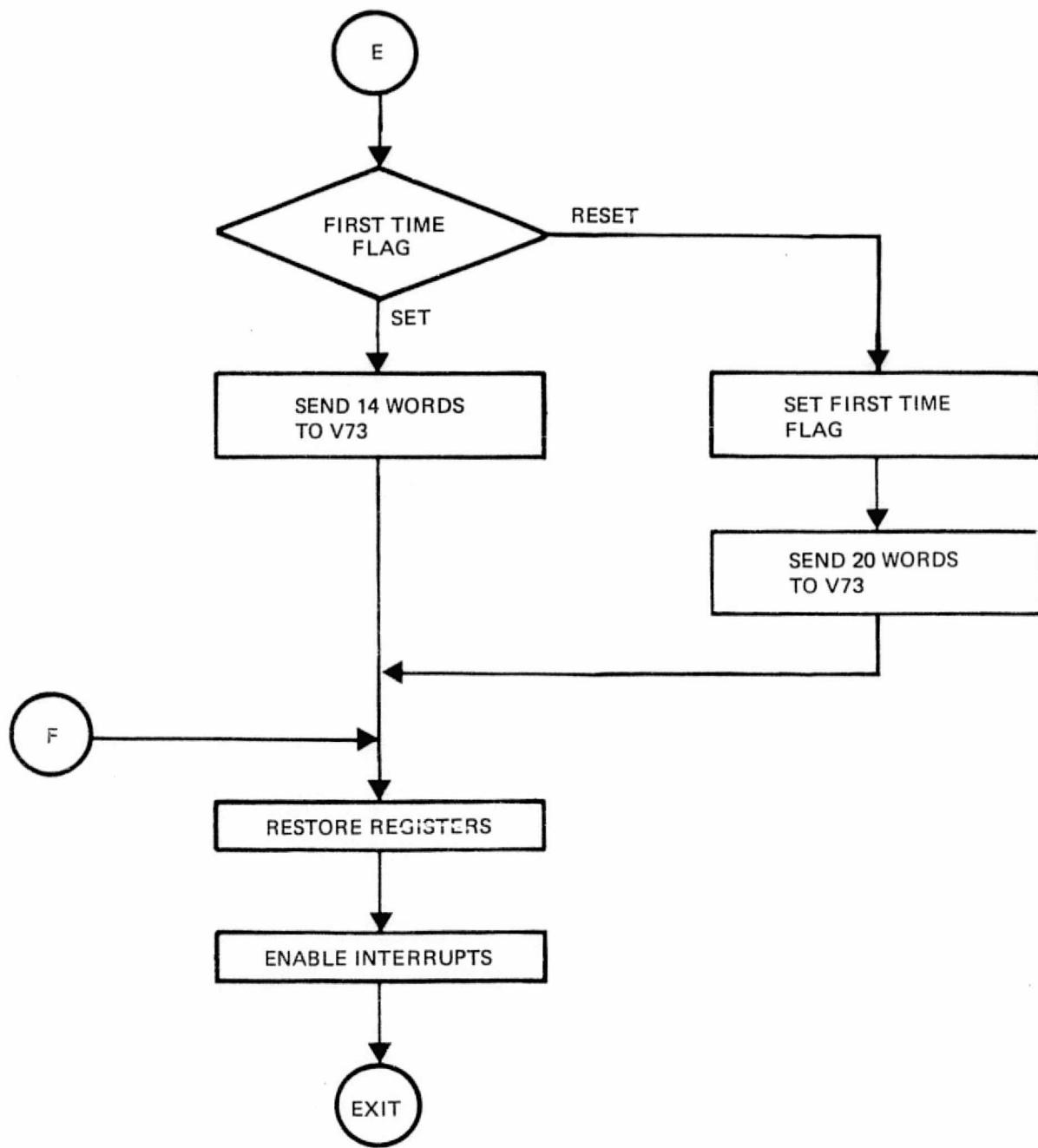
GWEN Program Flow Charts (4 of 7)



GWEN Program Flow Charts (5 of 7)



GWEN Program Flow Charts (6 of 7)



GWEN Program Flow Charts (7 of 7)